**US Army Corps
of Engineers**
Waterways Experiment
Station

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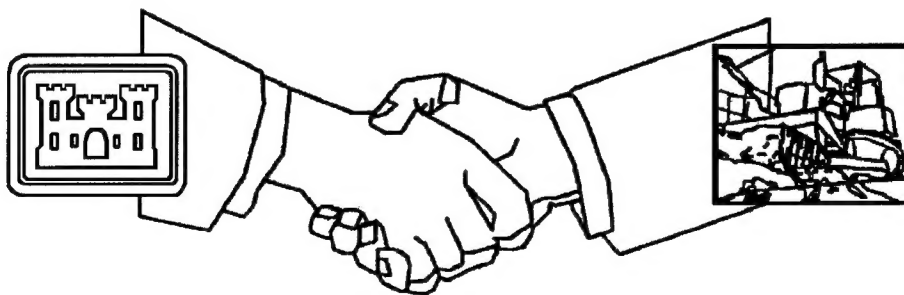
CONSTRUCTION PRODUCTIVITY ADVANCEMENT
RESEARCH (CPAR) PROGRAM

Reactive Powder Concrete for Producing Sewer, Culvert, and Pressure Pipes

by

Roy L. Campbell, Sr., Edward F. O'Neil,
William M. Dowd, Christophe E. Dauriac

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**A Corps/Industry Partnership to Advance
Construction Productivity and Reduce Costs**

Reactive Powder Concrete for Producing Sewer, Culvert, and Pressure Pipes

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Final report

US Army Corps
of Engineers
Waterways Experiment
Station

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STRUCTURES
LABORATORY

SCALE

500   0   500 m

AREA OF RESERVATION ‹ 2.7 sq km

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Preface

This report was prepared at the Structures Laboratory (SL), U.S. Army Engineer Waterways Experiment Station (WES), under the sponsorship of Headquarters, U.S. Army Corps of Engineers (HQUSACE), as a part of the Construction Productivity Advancement Research (CPAR) Program. The investigation reported in this document was conducted under a CPAR Cooperative Research and Development Agreement between WES and HDR Engineering, Inc. The HQUSACE Technical Monitors were Messrs. M. K. Lee, CECW-EG; G. Hughes, CECW-ET; and R. Chesi, CEMP-CE.

The study was conducted under the general supervision of Dr. Bryant Mather, Director, SL; Mr. John Ehrgott, Assistant Director, SL; and Dr. Paul F. Mlakar, Sr., Chief, Concrete and Materials Division (CMD), SL. Mr. William F. McCleese, CMD, was the CPAR point-of contact at WES. Mr. Edward F. O'Neil, CMD, was the Principal Investigator of this work unit.

The investigation by HDR Engineering, Inc., was conducted by Messrs. William M. Dowd and Christophe E. Dauriac. Other industry participants who provided invaluable assistance in the research effort include:

Elk River Concrete, Elk River, MN
Concrete Industries, Lincoln, NE
Gifford-Hill American, Grand Prairie, TX
International Pipe Machinery Corporation, Sioux City, IA
LaFarge Pipe and Precast, Gloucester, Ontario, CANADA
Nebraska Concrete Pipe Association, Omaha, NE
The Cretex Companies, Inc., Elk River, MN

Mr. Roy Campbell, Sr., CMD, and Mr. O'Neil, prepared the report. Technical support provided by CMD staff included: Ms. Bobbilyn Guerrero, who performed tests to determine rheology of paste; Ms. Linda Mayfield, who performed tests to determine direct shear properties; Mr. Cliff Gill, who collected modulus of elasticity data and performed tests to determine permeability and fatigue limits; Mr. Mike Lloyd, who prepared direct tensile specimens and performed tests to determine resistance to freezing and thawing; Mr. Jimmy Hall III, who performed tests to determine compressive, direct tensile, and flexural strengths; Mr. Mike Hedrick, who performed tests to

tensile, and flexural strengths; Mr. Mike Hedrick, who performed tests to determine compressive strength and fatigue limits; Mr. Melvin Sykes, who performed tests to determine resistance to sulfate attack; and Mr. Pete Burkes, who performed petrographic examinations to determine composition, size, and shape of various silica fumes and their effects on flow characteristics.

At the time for the publication of this report, Dr. Robert W. Whalin was the Director, WES. COL Robin R. Cababa, EN, was the Commander.

1 Introduction

Background

Reactive powder concrete

The innovative construction material that is the focus of this Construction Productivity Advancement Research (CPAR) project is Reactive Powder Concrete (RPC) 200. The RPC 200 is a very-high-strength, high-performance concrete material formulated to optimize those properties that are beneficial to, and minimize those properties that are detrimental to, strength, durability, permeability, and toughness of concrete. The initial formulation of RPC was developed by Bouygues S.A. in their laboratories in France. Engineers working for Bouygues mixed numerous trial batches of various combinations of cements, sands, silica fumes, and water-reducing admixtures and conducted fresh and hardened properties tests of these mixtures to determine which combinations provided the most optimal properties. They evaluated their results to choose a small number of optimized mixtures that they called reactive powder concrete. Table 1 presents material properties for RPC 200 mixtures developed by Bouygues (Richard and Cheyrezy 1995).

Table 1 Range of Mechanical Properties of RPC 200	
Compressive Strength of Cylinders	170 to 230 MPa
Flexural Strength	30 to 60 MPa
Fracture Energy	20,000 to 40,000 J/m^2
Ultimate Tensile Strain	$5{,}000 \times 10^{-6}$ to $7{,}000 \times 10^{-6}$ m/m
Young's Modulus	50,000 to 60,000 MPa

The compressive and flexural tensile strengths are on the order of 10 times that of 20 MPa concrete. The RPC 200 has Young's modulus of elasticity approximately 2.5 times the 20 MPa concrete and approximately twice as much strain capacity.

Reactive powder concrete obtains its name from the behavior and composition of its component materials. The component materials are the same as those that are normally found in conventional concrete and differ only in percentages. Cementitious materials are cement and silica fume, aggregates are sands, and water and high-range water-reducing admixtures (HRWRA) are used to hydrate the cementitious materials and provide fluidity to the mixture. When additional stiffness of the mixtures is required, silica flour can be added, and to provide flexural strength and toughness, steel fibers are incorporated.

Reactive powder concrete uses the word "powder" in its name to emphasize that all dry particles are kept to small powder sizes. This helps to promote its homogeneity. The word "reactive" is used in the name to indicate that it is formulated to maximize the effect of its reactive components. Much effort is taken to maximize the cementitious components of RPC. Table 2 describes the basic principles that were employed to obtain RPC's high-performance properties.

Table 2 Basic Formulation Principles of RPC	
Homogeneity	• Particle sizes and composition chosen for optimum effect • Reactive elements chosen for high silica content
Compactness	• Particle volumes and sizes chosen for optimum packing • Formulated to produce very low porosity
Microstructure	• High silica contents improves paste/aggregate homogeneity • Heat curing improves strength
Ductility	• Addition of micro-fibers provides ductility and toughness

Homogeneity is improved by striving to make as much of the dry component materials the same particle size as possible. All the dry components are less than 400 μm. Figure 1 shows the granulometry of particles in RPC. The largest component in RPC is the sand. The magnitude of the largest particle diameter for the sand is approximately 400 μm with an average size of 250 μm. The next largest particle size is the cement. Its diameter ranges from 75 μm to less than 10 μm. In RPC the average particle diameter for the cement is around 25 μm. The smallest dry particle in RPC is the silica fume with a particle size range from about 0.10 to 10 μm with an average of 0.25 μm. The remaining components are water and HRWRA, which are considered liquid components. The packing density of the particles helps elimination of pore spaces and provides an environment in which there are no major differences in the sizes of component materials.

The component materials are also chosen for their high silica content. The cement is selected to have a high $3CaO \cdot SiO_2$ content; silica fume is used in larger quantities than in regular concretes; and the sand is chosen to be a very pure silica sand. All these components provide extra volumes of silica that can potentially be converted to CSH gel during the hydration process. The compactness and chemical makeup of the hydrated paste produces a material that exhibits elastic properties very close to that of the silica aggregate. In a conventional concrete, the ratio of the elastic modulus of the aggregate to that

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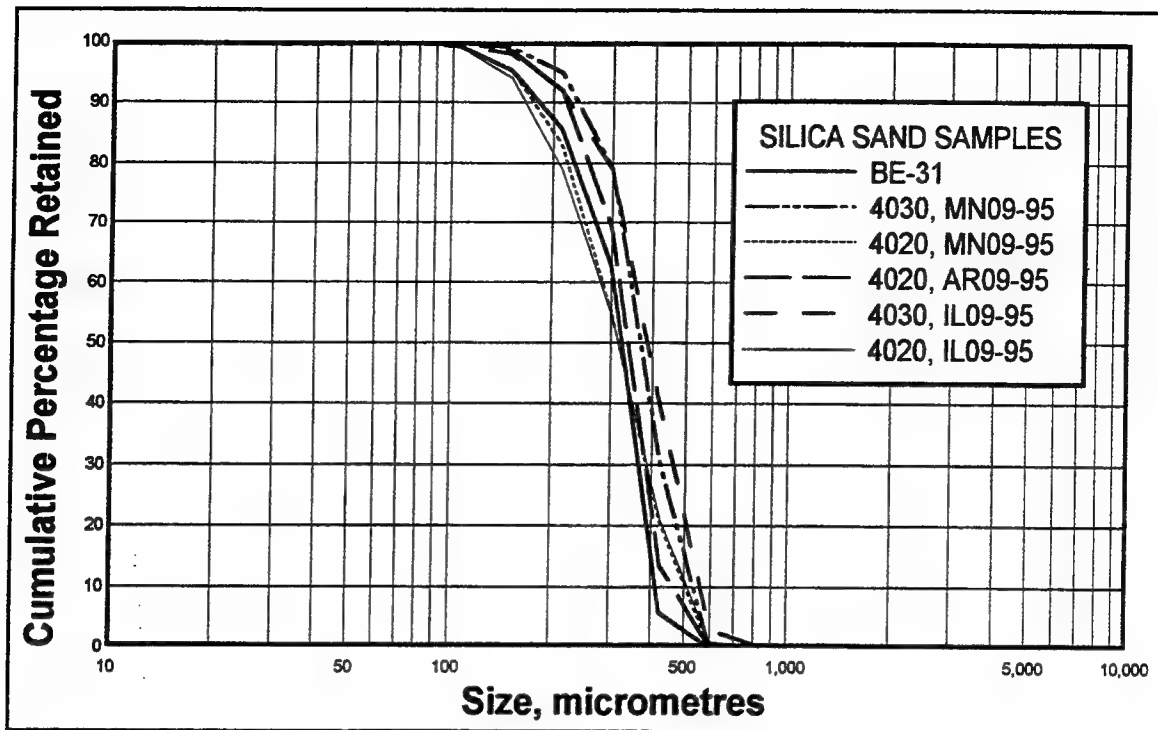
Figure 1. Grading of silica sands

of the paste can be as high as 3:1. As stress is applied to the hardened matrix, the paste and aggregate deform at different rates according to their respective moduli, which will lead to microcracking in the weak areas of the paste. This normally occurs in the weaker paste at the surface of the aggregate particle. RPC strives to bring this ratio closer to 1 to ensure that the paste and aggregate move together and less differential strain is imparted at the paste-aggregate surface.

Material compactness is emphasized in RPC to minimize the void spaces in the paste. The greater the number of voids in the matrix, the greater the number of sites for the initiation of microcracks, and the sooner the onset of cracking under a given stress regime. Compactness is accomplished in several ways. The volumes of the small particles are chosen to maximize the particle packing density of RPC. The volumes of sand, cement, silica flour, and silica fume have been chosen to ensure that the spaces between larger particles are filled with a sufficient volume of smaller particles. The most evident example of this is the cement and silica-fume relationship. The spaces between cement particles in the paste are filled by the much smaller silica-fume particles. Because these spaces are filled, there is less of a chance that there will be a void where cracking can initiate.

The amount of water used to hydrate RPC also plays a role in maximizing compactness and minimizing void spaces. Good-quality conventional concrete and high-strength concrete use a water-to-cement ratio (w/c) on the order of 0.40 to 0.45. According to Powers (1964), the w/c needed to hydrate all the cement in the mixture is 0.38. The water that is present in excess of that

needed to hydrate the cement is trapped in the concrete during the hydration process and forms the voids that ultimately lead to microcracking of the cement paste. The w/c used in RPC ranges from 0.15 to approximately 0.25. As will be discussed further in this report, this range of w/c's not only produces the highest range of strengths but also ensures that all the water in the mixture will be combined in producing CSH and will not be left behind to form voids.

CPAR cooperative agreement

In 1995 the U.S. Army Engineer Waterways Experiment Station (WES) and HDR Engineering, Inc., signed a CPAR Cooperative Research and Development Agreement (CPAR-CRDA) to begin a multi-year joint research project to develop RPC in the United States and to direct the first uses of this material to making concrete sewer and culvert pipe products for the U.S. construction industry. Because of the potential benefits of this high-performance concrete material to both the Federal Government and the construction industry, this research was considered to be well suited to the CPAR Program.

The CPAR partner with the Corps of Engineers under this project is HDR Engineering, Inc., a wholly owned subsidiary of HDR, Inc., of Omaha, NE, an internationally known architectural/engineering design firm. HDR Engineering, Inc., as one of the tripartite arms of HDR, Inc., itself has an international reputation in the areas of transportation, water/wastewater, and waste/energy. It is nationally situated with headquarters in Omaha and has offices in 36 cities in 25 states. Its transportation experience includes roadway, railroad, airport, and bridge engineering. It has expertise in both concrete and steel structural design, and its water and wastewater experiences include services in stormwater management, hydropower, groundwater and water systems, sewer and pumping station design, sewer collection systems, and industrial and medical waste storage systems.

While HDR, Inc., has been a U.S. engineering company since 1917, it became a part of the international design/building firm of Bouygues S.A. in 1983. Bouygues is one of Europe's largest construction firms and ranks in the top 10 engineering and construction firms in the world. Its expertise encompasses building construction, transportation, renovation and restoration, architectural and engineering design, and construction as well as presences in communication and entertainment. During the 1980's, Bouygues devoted considerable research and development effort in developing very high-strength concretes for its European construction markets. Bouygues chose its newly acquired U.S. engineering firm, HDR Engineering, Inc., to represent the development of RPC in the United States under the CPAR Program.

Objective of Research

The objective of this research was to develop and demonstrate the technical and economic viability of RPC for producing precast sewer, culvert, and pressure pipes and precast piling with the ultimate program goals of gaining

construction industry acceptance and implementing wide-scale commercial fabrication of these products within 3 years. The objective was revised in June 1997 to eliminate any additional efforts to produce precast pile products based on an economical analysis of their competitiveness with existing pile systems.

Research Plan

The research was scheduled for four phases at the onset of the project. Phase I involved the development and enhancement of RPC 200 mixtures for producing precast pipes and piling, using initial RPC criteria established by Bouygues. Pertinent technical papers and literature plus mixing and casting procedures conducted at Bouygues were to be provided by HDR as the initial technology transfer between industry and WES researchers. WES and HDR were to work together to reproduce mixtures using U.S. materials and where possible make improvements to the formulation mixtures. WES was to make laboratory specimens according to the formulations provided by HDR and to analyze specimens. Tests were to include basic material property tests, performance characteristics tests, and chemical and petrographic tests.

Phases II and III were to entail the fabrication and evaluation of prototype specimens for each of the precast products. Trial RPC 200 batches were to be mixed at plant sites to verify material production feasibility. Samples from RPC produced at plant sites were to be evaluated to determine the chemical resistance of RPC to sulfuric acid and magnesium and sodium sulfate solutions. WES and HDR were to initiate prototype product evaluations in conjunction with the industry participants for each of the research products. Full-scale prototypes were to be made to evaluate the production process as well as to produce specimens for testing and evaluation. Product performance testing was to be conducted to verify prototype conformance with industry standards. The production of prototypes was to be evaluated to determine its economic viability and commercialization potential.

The final phase was to be the commercialization and transfer of the developed RPC precast technology. To gain acceptance for RPC products, technical papers were to be presented at national conferences and through trade publications and engineering journals. After the research team developed a high level of confidence in products, demonstration projects were to be arranged. Using the successful demonstration projects as a basis, RPC technology was to be marketed nationally.

2   Materials

The criteria employed to screen potential materials for use in RPC prototype mixtures were based on previous work and experiences by Bouygues and HDR. Additional screenings and final selections of materials were made by HDR using results of experiments conducted at WES. The primary means of evaluation was through testing of trial mixtures to determine the potential of a material for producing optimum rheology and strengths in prototype mixtures. Cost was the deciding factor for final material selection when the differences in properties between materials were considered tolerable.

Cement

Criteria used to select potential cements for evaluation were developed by HDR and were as follows:

$CaO/SiO_2 \equiv$ C/S Ratio	less than	3.10
$3CaO \cdot Al_2O_3 \equiv C_3A$	less than	7%
$3CaO \cdot SiO_2 \equiv C_3S$	greater than	55%
$3CaO \cdot Al_2O_3 + 4CaO \cdot Al_2O_3 \cdot Fe_2O_3 \equiv$ $C_3A + C_4AF$	less than	20%
Blaine Specific Surface	range of	260 - 340 m^2/kg

Mill test reports were solicited from cement manufacturers and evaluated against the selection criteria. A summary of the evaluation of mill test reports is presented in Table 3. In the table, a cement ingredient and the cement were flagged as "fail" if the ingredient content did not meet criteria or was not furnished ("N/A").

WES personnel performed tests to determine compressive strength, density, and rheology for mixtures containing cements meeting the mill test criteria. Based on these results, it was concluded that the Lafarge Oilwell H cement gave results very close to the cements used by Bouygues (Dauriac 1995a). The Holnam Oilwell H and the Southdown Type V cements were considered alternatives with the Southdown cement ranked lower based on its higher water demand.

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Table 3
Screenings of Mill Test Reports for Cement Acceptance

Manufacturer	Test Date	Cement Plant	Cement Type	CaO %	SiO₂ %	CaO/SiO₂ Ratio [a]	C₃A % [b]	C₂S %	C₃S % [c]	C₄AF %	C₃A + C₄AF (%) [d]	Blaine Specific Surface (m²/kg) [e]	Overall pass/fail
Ash Grove Cement Co.	2/2/95	Louisville, NE	II	62.55	21.06	2.97	7 (fail)	21	52 (fail)	10	17	375 (fail)	fail
Calif. Portland Cement Co.	3/17/95	Mojave, CA	Oil Well G, low alk.	64.76	22.18	2.92	4	21	56	N/A	N/A (fail)	324	pass
Dacotah Cement	10/4/94	Rapid City, SD	II	N/A	20.00	N/A (fail)	8 (fail)	N/A	N/A (fail)	N/A	N/A (fail)	280	fail
Dacotah Cement	10/4/94	Rapid City, SD	V	N/A	N/A	N/A (fail)	5	N/A	N/A (fail)	N/A	N/A (fail)	280	fail
Holnam Inc.	10/4/94	Mason City, IA	I/II	63.20	20.60	3.07	6	17	56	12	18	380 (fail)	fail
Holnam Inc.	2/6/95	Ada, OK	V	65.00	22.00	2.95	4	20	58	13	17	354 (fail)	fail
Holnam Inc.	1/6/95	Theodore, AL	I/II	64.40	20.90	3.08	6	14	61	11	17	392 (fail)	fail
Holnam Inc.	12/29/94	Midlothian, TX	II	64.20	21.00	3.06	7 (fail)	19	53 (fail)	N/A	N/A (fail)	347 (fail)	fail
Holnam Inc.	11/1/94	Midlothian, TX	HPC	56.50	28.90	1.96	N/A (fail)	N/A	N/A (fail)	N/A	N/A (fail)	380 (fail)	fail
Holnam Inc.	7/28/94	Mason City, IA	I	63.00	19.70	3.20 (fail)	8 (fail)	12	61	10	18	370 (fail)	fail
Holnam Inc.	1/11/95	Midlothian, TX	I	64.50	20.10	3.21 (fail)	11 (fail)	17	54 (fail)	N/A	N/A (fail)	332	fail
Holnam Inc.	7/20/93	Artesia, MS		N/A	20.78	N/A (fail)	8 (fail)	N/A	N/A (fail)	N/A	N/A (fail)	342 (fail)	fail
Holnam Inc.	5/25/95	Ada, OK	Class H (HSR)	65.00	22.60	2.88	2	21	58	12	14	274	pass
Holnam Inc.	10/25/94	Ada, OK	Class H (HSR)	64.00	22.00	2.91	2	19	58	12	14	281	pass
Kaiser Cement Corp.	N/A	Cupertino, CA	V	66.05	22.16	2.98	3	15	65	12	15	339	pass
Kaiser Cement Corp.	N/A	Cupertino, CA	I, II	64.32	21.59	2.98	3	20	56	12	15	328	pass
Kaiser Cement Corp.	N/A	Cupertino, CA	V Low Alkali	65.50	22.08	2.97	4	17	62	12	16	319	pass
Lafarge Corporation	1/27/95	Grand Chain, IL	I, II, Low Alkali	64.19	21.98	2.92	6	19	58	N/A	N/A (fail)	367 (fail)	fail
Lafarge Corporation	1/27/95	Alpena, MI	I	64.30	21.70	2.86	9 (fail)	22	53 (fail)	N/A	N/A (fail)	374 (fail)	fail
Lafarge Corporation	1/27/95	Alpena, MI	IA	64.20	21.50	2.99	9 (fail)	22	52 (fail)	7	16	385 (fail)	fail
Lafarge Corporation	1/27/95	Alpena, MI	III	64.00	21.50	2.98	9 (fail)	23	51 (fail)	N/A	N/A (fail)	634 (fail)	fail
Lafarge Corporation	1/27/95	Bath, MI	III	61.60	20.80	2.96	9 (fail)	29	41 (fail)	N/A	N/A (fail)	516 (fail)	fail
Lafarge Corporation	1/27/95	Woodstock, MI	III	62.90	21.00	3.00	12 (fail)	26	46 (fail)	N/A	N/A (fail)	596 (fail)	fail
Lafarge Corporation	10/5/94	Kansas City, KS	II	63.20	21.80	2.90	3	22	54 (fail)	N/A	N/A (fail)	344 (fail)	fail
Lafarge Corporation	1/27/95	Bath, MI	I	63.50	22.00	2.89	7 (fail)	27	48 (fail)	N/A	N/A (fail)	363 (fail)	fail
Lafarge Corporation	1/27/95	Bath, MI	I/II	63.50	22.00	2.89	7 (fail)	27	48 (fail)	N/A	N/A (fail)	363 (fail)	fail
Lafarge Corporation	1/27/95	Bath, MI	II	63.50	22.00	2.89	7 (fail)	27	48 (fail)	N/A	N/A (fail)	363 (fail)	fail
Lafarge Corporation	1/27/95	Fredonia, KS	I, II, Low Alkali	62.70	21.20	2.96	5	20	54 (fail)	13	18	345 (fail)	fail
Lafarge Corporation	1/27/95	Woodstock, MI	I, Low Alkali	62.60	21.70	2.88	7 (fail)	27	47 (fail)	N/A	N/A (fail)	387 (fail)	fail
Lafarge Corporation	1/27/95	Woodstock, MI	II, Low Alkali	62.60	21.70	2.88	7 (fail)	27	47 (fail)	N/A	N/A (fail)	387 (fail)	fail
Lafarge Corporation	1/27/95	Davenport, IA	I, II	63.40	20.35	3.12 (fail)	8 (fail)	14	59	10	17	379 (fail)	fail
Lafarge Corporation	1/27/95	Davenport, IA	I, II, Low Alkali	63.70	20.13	3.16 (fail)	7 (fail)	12	61	N/A	N/A (fail)	380 (fail)	fail
Lafarge Corporation	1/27/95	Fredonia, KS	I, Low Alkali	63.40	20.30	3.12 (fail)	10 (fail)	14	59	9	19	344 (fail)	fail
Lafarge Corporation	1/27/95	Paulding, OH	I	64.10	20.30	3.16 (fail)	10 (fail)	14	58	8	N/A (fail)	360 (fail)	fail
Lafarge Corporation	2/3/95	Alberta, Canada	Exshaw Oil Well G	N/A	N/A	2.90	2	N/A	57	13	15	328	pass
Lafarge Corporation	2/3/95	Grand Chain, IL	Joppa Oil Well H	N/A	N/A	3.00	1	N/A	60	15	16	305	pass
Lehigh Portland Cement Co.	7/9/94	Mason City, IA	III	63.60	21.10	3.01	10 (fail)	22	51 (fail)	N/A	N/A (fail)	540 (fail)	fail
Lehigh Portland Cement Co.	6/9/94	Mason City, IA	I	63.90	21.20	3.01	10 (fail)	22	51 (fail)	N/A	N/A (fail)	350 (fail)	fail
Lehigh Portland Cement Co.	1/27/95	Union Bridge, MD	I/II	63.50	21.60	2.94	8 (fail)	22	53 (fail)	N/A	N/A (fail)	366 (fail)	fail
Lone Star Ind., Inc.	1/26/95	Pryor, OK	I/II	64.30	21.05	3.05	5	18	57	13	18	355 (fail)	fail
Lone Star Ind., Inc.	10/6/94	Sweetwater, TX	Class H	64.60	23.00	2.81	3	24	54 (fail)	4	7	220 (fail)	fail
North Texas Cement Co.	12/21/94	Midlothian, TX	I	65.00	20.40	3.19 (fail)	10 (fail)	13	60	9	19	367 (fail)	fail
North Texas Cement Co.	12/21/94	Midlothian, TX	II	65.15	20.58	3.17 (fail)	7 (fail)	13	61	12	19	354 (fail)	fail
Southwestern Portland Cement	1/27/95	Odessa, TX	C	64.30	20.86	3.08	N/A (fail)	12	63	N/A	N/A (fail)	390 (fail)	fail
Southwestern Portland Cement	1/27/95	Odessa, TX	I/II	64.89	20.40	3.18 (fail)	6	9	65	N/A	N/A (fail)	364 (fail)	fail
Texas Industries, Inc.	7/20/93	Midlothian, TX	I	64.33	20.51	3.14 (fail)	6	16	57	12	18	326	fail

Note: Specifications for RPC cements: [a] CaO/SiO_2 <3.10; [b] C_3A < 7%; [c] C_3S > 55%; [d] C_3A+C_4AF < 20%; [e] Blaine Specific Surface in the range of 260 - 340 m²/kg

Silica Fume

Criteria used to select potential silica fumes for evaluation were developed by HDR and were as follows:

Silica content	Greater than	92%
Carbon content	Less than	2%
Loss on ignition (LOI)	Less than	2%
Grain size distribution		Monodispersive
	Upper limit	(0.5 - 1 μm)

To supplement the evaluation, WES personnel performed petrographic examinations of 11 silica fumes (Appendix A) to determine chemical and physical features that may have contributed to observed differences in flow. In general, the dark-colored fumes had smoother surfaces and more unfused (spherical) particles than the light-colored fumes. The dark-colored fume samples also had less crystalline phase and more glass and were considered more reactive. The relationship between chemical and physical features and flow characteristics of each fume could not be clearly established. However, it was suspected that the less reactive (more crystalline) a fume was, the better its flow characteristics.

WES personnel performed tests to determine compressive strength, density, and rheology for mixtures containing silica fumes meeting HDR's criteria. Based on these results, it was concluded that the Elkem ES 900W was considered the equivalent to the MST zirconium silica fume used by Bouygues (Dauriac 1995a). Among the U.S. alternative non-zirconium fumes (more grey fumes) tested, Norchem GM undensified provided the best results. Both the Elkem EMS 965 and the Norchem low-densified fumes were considered as second alternative to other non-zirconium fumes.

Silica Sand

A pure silica sand was designated for use by HDR so that the modulus of elasticity for the aggregate was near that for the paste. The gradings were determined by WES investigators for a number of silica sands. These gradings along with the distribution for the sand used by Bouygues (BE-31) are shown in Table 4 and Figure 1. Flows (American Society for Testing and Materials (ASTM) C 230 (ASTM 1995e)) and compressive strengths (ASTM C 109 (ASTM 1995c)) were also determined for mixtures containing different sands. Flow and strength results for Granusil 4020 and Granusil 4030 sand are depicted in Figure 2.

Based on prior testing at Elk River Concrete in September 1994 and tests performed by WES personnel, the Granusil 4020 and Granusil 4030 were considered good alternatives to the sand used by Bouygues (Dauriac 1995a). Tests performed by WES personnel also showed the local chert sand to be compatible to RPC technology.

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Table 4
Grading of Silica Sands

Sieve Size (μm)	Cumulative Percentage Retained					
	BE 31	4030 MN09-95	4020 MN09-95	4020 AR09-95	4030 IL09-94	4020 IL09-94
850	--	--	--	0.0	0.0	0.0
600	0.0	0.0	0.0	0.1	3.0	1.0
425	5.7	30.0	20.3	13.5	39.0	21.0
300	62.8	79.0	55.2	69.2	79.0	55.0
212	85.7	95.0	83.1	92.0	92.0	79.0
150	95.3	99.0	95.4	98.5	98.0	94.0
106	99.1	99.9	99.1	99.9	99.4	99.0
75	100.0	100.0	100.0	100.0	99.5	100.0
53	--	--	--	--	100.0	--
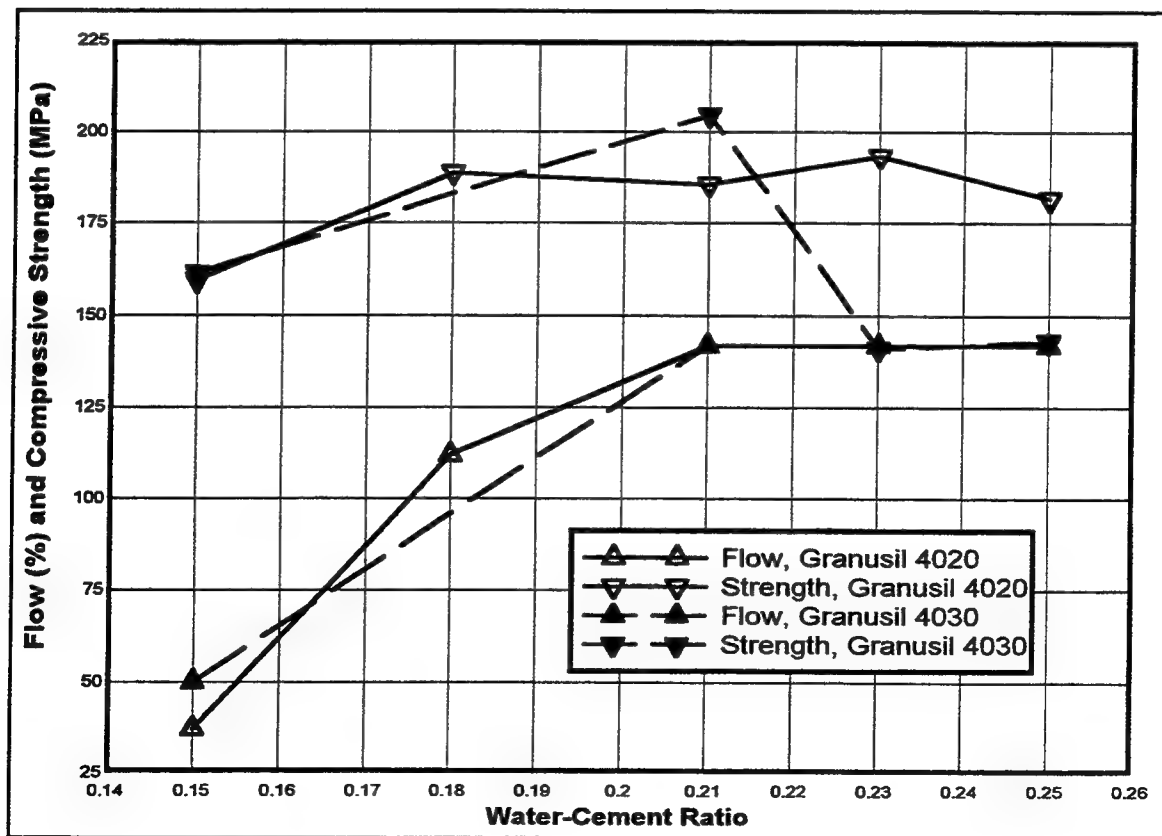
Figure 2. Flows and compressive strengths for mixtures containing Granusil 4020 and 4030 sands

Fibers

Criteria used to select potential fibers for evaluation were developed by HDR and were as follows:

Material	High-strength carbon steel
	(If coated, coating to be nonferrous or metal alloy)
Diameter	150 to 300 μm (150 to 180 μm optimal)
Length	10 to 16 mm (12 to 14 mm optimal)
Strength	Greater than 850 MPa

The Bekaert OL 13/.16 fibers were selected for evaluation. Novocon Recycled Tire Cord Fibers and Novocon Novotex Fibers were also selected for evaluation based on their lower cost.

High-Range Water-Reducing Admixture (HRWRA)

Flows (ASTM C 230) and compressive strengths (ASTM C 109) were determined for mixtures batched using different HRWRA's. Results for three types of HRWRA's (naphthalene sulfonate sodium salt [Disal], naphthalene sulfonate calcium salt [Durasar], and sodium melamine sulfonate [Meladyne]) are depicted in Figure 3 for mixtures having a w/c of 0.20.
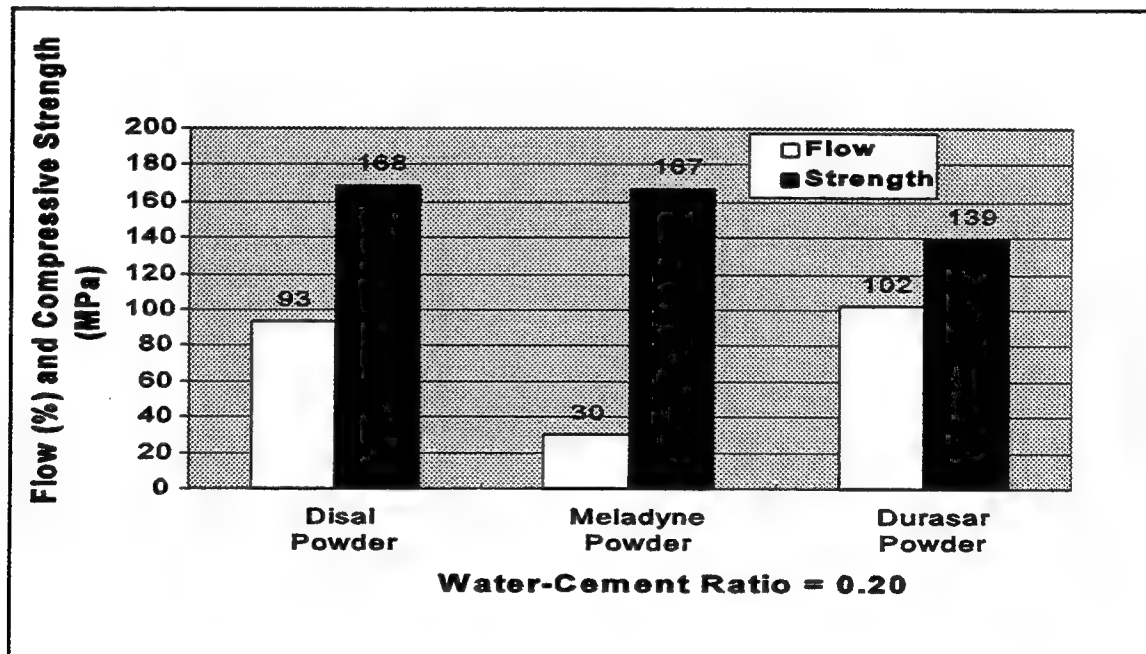
Figure 3.   Flows and compressive strengths for mixtures containing different HRWRA's

The Disal HRWRA was selected as the alternative to the polyacrylate dispersant HRWRA (Mapei Fluide X-404) used by Bouygues. Flows and

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compressive strengths were determined for mixtures batched using either the dry or liquid forms of the Disal HRWRA. Specimens tested at 7- and 28-day ages were demolded the day after casting and placed in lime water until tested. Specimens tested at 13-day age were demolded the day after casting and cured for 6 days in lime water at 20° C, 4 days in hot water at 90° C, and 2 days in hot air at 90° C.

Test results presented in Tables 5 and 6 and Figures 4 and 5 showed that RPC mixtures batched with the powder form of Disal yielded higher mortar flows than those batched with the liquid form of Disal. The compressive strength results for 13-day specimens were higher than those for 7-day and 28-day specimens due to heat curing of the 13-day specimens. The compressive strengths for 28-day specimens were greater than those for 7-day specimens, except for batches 980205 and 980206. It was concluded that the 28-day results for batch 980205 was not representative, and therefore, should be disregarded.

Silica Flour

HDR-designated particle sizes equivalent to those found in the French silica flours were used by Bouygues as criteria for selection of potential U.S. flours for evaluation. The equivalent particle sizes were as follows:

Sifraco C400	Particle Size (Sedigraph)
Top size	Approximately 10 μm
Median size d_{50}	Approximately 4 μm
Sifraco C500	
Top size	Approximately 40 μm
Median size d_{50}	Approximately 10 μm

WES performed tests to determine compressive strength, density, and rheology for mixtures containing silica flours meeting HDR's criteria. Based on these results, it was concluded that Minusil 10 (top size of 10 μm) and Minusil 40 (top size of 40 μm) would provide a stiff mixture while maintaining compressive strength for dry-cast mixtures. The Minusil 40 was considerably cheaper, and thereby, preferred.

Table 5
Evaluation of Liquid and Powder Forms of HRWRA (Disal) for RPC Wet Mixture

HRWRA	Water-Cement Ratio	Mass Relative to Cement	Time to Paste m:s	Wet Mixing Time m:s	Flow (ASTM C 230[2]), %	Batch Number	Mass In Air g	Mass In Water g	Density g/mL	Comp. Strength (ASTM C 109[1]) 7-days Age, MPa	13-days Age, MPa	28-days Age, MPa
Liquid	0.170	0.015	7:05	8:0	82	980205	316.0	187.0	2.45	127	135	103
							316.6	187.5	2.45	115	197	99
							318.5	188.5	2.45	135	191	122
								Average	2.45	126	174	108
		0.018	6:15	12:30	82	980206	316.0	186.8	2.45	127	156	105
							318.6	188.8	2.45	112	156	134
							318.7	188.7	2.45	125	186	120
								Average	2.45	122	166	120
		0.021	5:55	11:50	82	980207	316.7	187.2	2.45	96	208	133
							318.8	188.5	2.45	95	164	130
							317.5	187.5	2.44	56	175	139
								Average	2.44	82	182	134
Powder	0.170	0.015	5:35	11:10	90	980211	316.5	187.1	2.45	127	192	137
							315.4	185.9	2.44	116	203	140
							317.4	187.5	2.44	116	182	138
								Average	2.44	120	192	138
		0.018	5:00	10:00	92	980212	314.9	185.5	2.43	120	163	123
							316.1	185.8	2.43	115	161	126
							318.0	187.6	2.44	114	156	121
								Average	2.43	116	160	124
		0.021	4:30	9:00	95	980213	315.7	185.5	2.42	116	182	119
							315.7	185.3	2.42	111	184	104
							315.4	185.6	2.43	107	151	120
								Average	2.43	111	172	115

[1] ASTM 1995c.
[2] ASTM 1995e.

Table 6
Evaluation of Liquid and Powder Forms of HRWRA (Disal) for RPC Dry Mixture

HRWRA	Water-Cement Ratio	Mass Relative to Cement	Time to Paste m:s	Wet Mixing Time m:s	Flow (ASTM C 230[2]), %	Batch Number	Mass			Comp. Strength (ASTM C 109[1])		
							In Air g	In Water g	Density g/mL	7-days Age, MPa	13-days Age, MPa	28-days Age, MPa
Liquid	0.220	0.015	8:05	16:10	70	980225	312.7	182.3	2.40	121	159	140
							315.3	185.0	2.42	125	125	130
							315.2	184.7	2.42	126	150	131
							Average			124	145	134
		0.018	7:55	15:50	75	980226	315.1	184.0	2.40	129	181	126
							313.1	183.1	2.41	133	166	131
							313.6	183.4	2.41	123	169	131
							Average			128	172	129
		0.021	6:15	12:30	80	980227	315.9	185.0	2.41	112	152	137
							312.9	182.6	2.40	107	194	130
							307.3	179.9	2.41	117	203	134
							Average			112	183	134
Powder	0.220	0.015	5:00	10:00	101	980228	314.0	182.5	2.39	98	142	123
							310.3	180.0	2.38	109	163	102
							312.3	182.3	2.40	103	179	134
							Average			103	161	120
		0.018	4:35	9:10	103	980229	312.6	181.7	2.39	76	224	123
							313.1	182.4	2.40	98	203	139
							311.6	182.1	2.41	94	182	131
							Average			89	203	131
		0.021	4:30	9:00	106	980230	311.1	182.1	2.40	89	184	113
							314.8	184.1	2.41	105	161	128
							313.9	183.9	2.41	107	176	131
							Average			100	174	124

[1] ASTM 1995c.
[2] ASTM 1995e.
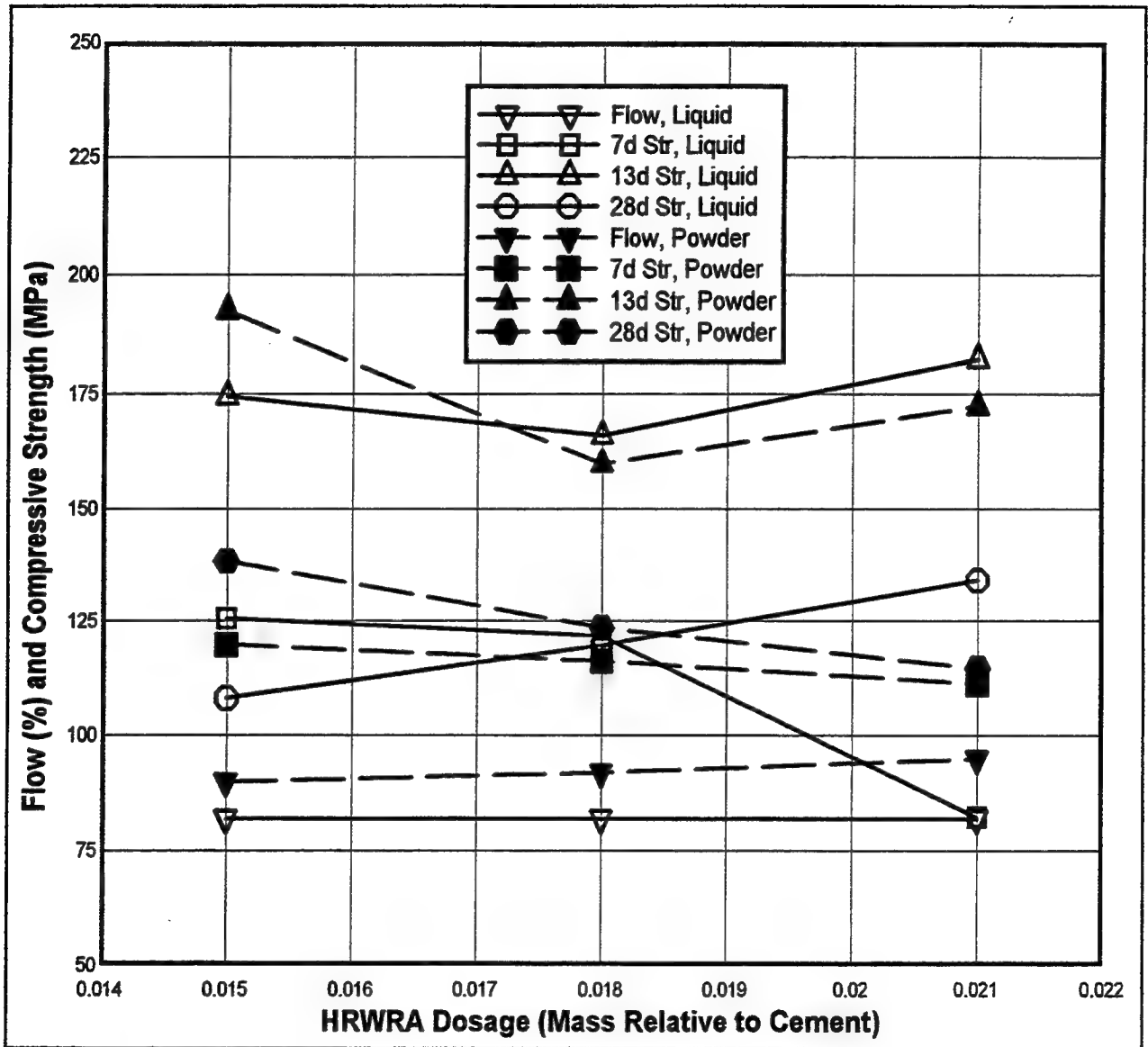
Figure 4.   Flows and compressive strengths for mixtures containing liquid or dry Disal HRWRA at a w/c of 0.17
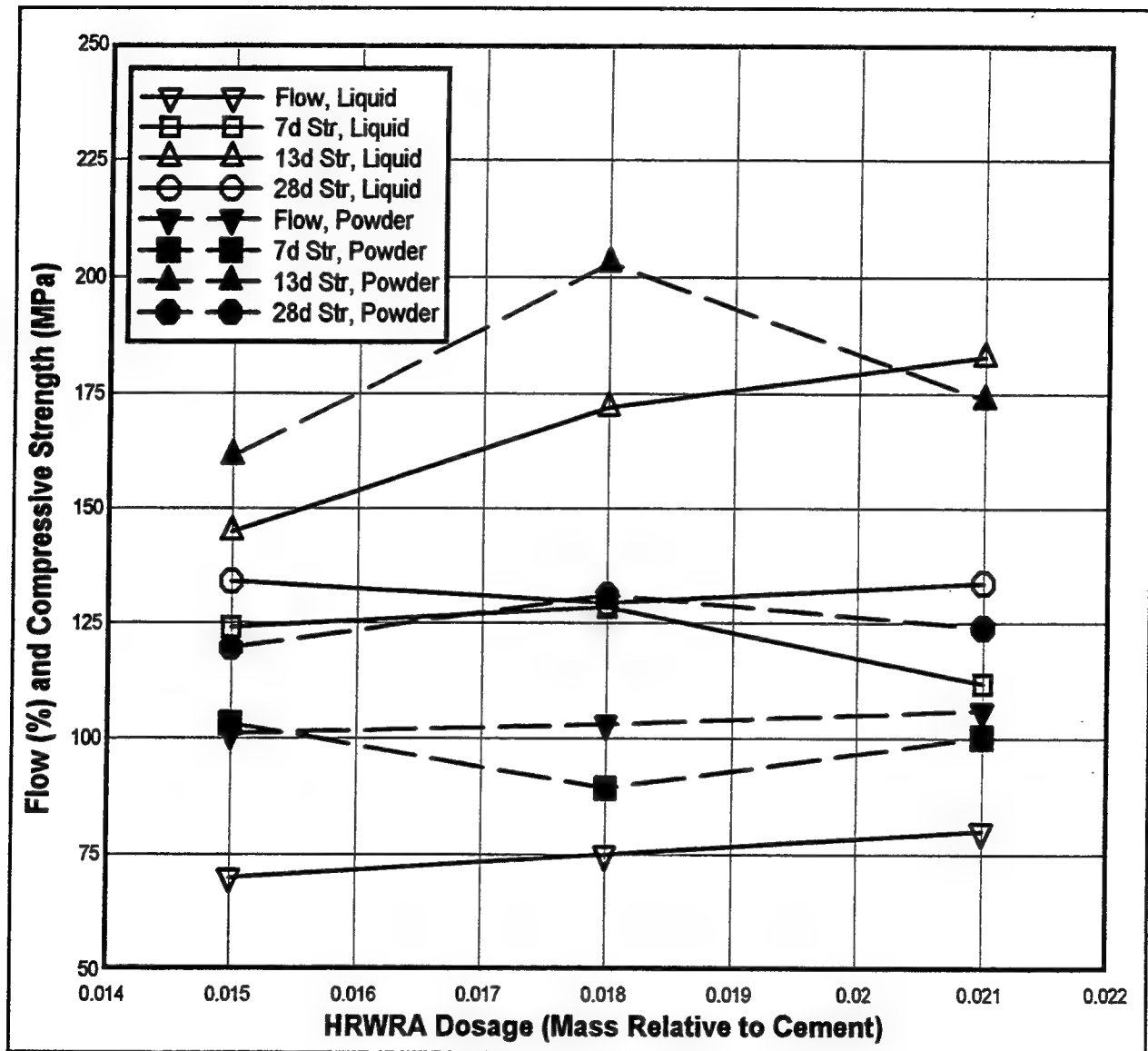
Figure 5. Flows and compressive strengths for mixtures containing liquid or dry Disal HRWRA at a w/c of 0.21

3 Mixtures

Two mixtures, one flowable and the other zero slump, were selected as representative of RPC pipe production mixtures. The flowable mixture was designated as the wet mixture and the zero-slump mixture as the dry mixture. Hardened concrete properties were determined for both mixtures. The proportions for wet and dry mixtures are presented in Table 7, and the summary of hardened properties are presented in Table 8.

Other evaluations performed but not listed in Table 8 include the determination of the resistance of RPC to cavitation erosion and sulfate attack. Cavitation specimens were made using the wet mixture, and sulfate specimens were made using the dry mixture, in which the w/c had been increased from 0.175 to 0.190.

The general procedure for mixing batches was as follows:

- Load mixer with (a) cement, (b) fume, (c) flour, and (d) sand, respectively.

- Mix for 1 min.

- Load mixer with water containing half HRWRA dosage.

- Load mixer with remaining half of HRWRA.

- Mix until paste forms.

- Load fibers.

- Mix for a time equal to twice the time required to reach paste.

Specimens were removed from the forms after 24 hr and cured for 12 days (6 days in limewater at 20° C, 4 days in hot water at 90° C, and 2 days in hot air at 90° C). The curing was the same as used in the experiments by Bouygues to determine hardened properties for RPC 200.

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Table 7
Proportions for RPC Wet and Dry Mixtures

Material	Product	Bulk Specific Gravity	Wet Mixture[1]		Dry Mixture[2]	
			Relative Mass	Mass per m³ of Mixture, kg	Relative Mass	Mass per m³ of Mixture, kg
Cement	Holna Oilwell H/Ada	3.21	1.000	942	1.000	728
Silica Fume	Elkem EMS 900W	2.34	0.250	236	0.325	237
Silica Flour	Minusil 10	2.30	0.000	0	0.300	218
Fine Aggregate	Granusil 4030	2.65	1.100	1,036	1.450	1,056
Fibers	Bekaert OL13/.16	7.70	0.170	160	0.222	
	w/c = 0.170	1.00	0.144	136	--	--
	w/c = 0.175	--	--	--	0.150	109
Water	w/c = 0.190	--	--	--	0.165[2]	120[2]
HRWRA	Disal Liquid (59% water)	1.21	0.044	41	0.043	31

[1] Total free air 2 percent of mixture volume.
[2] Sulfate-attack specimens.

Table 8
Summary of Hardened Property Test Results for RPC Mixtures

Property	Test Method	Wet Mixture	Dry Mixture
Compressive Strength, MPa	ASTM C 39 (ASTM 1995a)	214	237

Direct Shear Strength
  Angle of Internal Friction, degree
  Cohesion, MPa
	RTH-203
	RTH-203
	(WES 1990)
		--[1]
		--
			--[1]
			--

Direct Tensile Strength, MPa	CRD C 164 (WES 1949b)	8.1	8.2
Durability Factor after 300 Cycles of Freezing and Thawing, %	ASTM C 666, Procedure A (ASTM 1995i)	99.9	99.8
Fatigue Strength at 2-Million Cycles as a percentage of Flexural Strength	ASTM C 78[2] (ASTM 1995b)	48	47
Flexural Strength, MPa	ASTM C 78 (ASTM 1995b)	40	33
Modulus of Elasticity, MPa	ASTM C 469 (ASTM 1995f)	56,100	59,900
Permeability, Darcy	CRD C 163 (WES 1949a)	0	0

[1] Results were inconclusive.
[2] Test same as specified in ASTM except applied stress was a percentage of ultimate and was cyclic.

Compressive Strength and Modulus

Ten, 76-mm-diam by 152-mm-high cylindrical specimens were tested to determine the compressive strength (ASTM C 39 (ASTM 1995a)) and modulus of elasticity (ASTM C 469 (ASTM 1995f)) for the hardened concrete mixtures after curing. The results of these tests are presented in Table 9. The average values for compressive strength and modulus of elasticity are comparable with those developed by Bouygues (Table 1).

Table 9
Compressive Strength (ASTM C 39[1]) and Modulus of Elasticity (ASTM C 469[2]) for RPC Wet and Dry Mixtures

Mixture	Specimen	Compressive Strength, MPa	Modulus of Elasticity, MPa
Wet	970403-1	226	55,300
	970403-2	213	59,700
	970403-3	210	54,600
	970403-4	211	54,700
	970404-1	213	55,600
	970404-2	212	56,500
	Average	214	56,100
Dry	970406	215	56,300
	970443	228	60,800
	970457	272	63,300
	970458	234	59,200
	Average	237	59,900

[1] ASTM (1995a).
[2] ASTM (1995f).

Direct Shear Strength

Twenty-one, 76-mm-diam by 152-mm-high cylindrical specimens were tested to determine the direct shear strength (RTH-203) for the hardened concrete mixtures after curing. The ultimate strengths (Table 10) were determined at normal stresses of 0.4, 0.8, and 1.6 MPa. Linear regression curve fits (Figure 6) are used to depict the relationship between shear strength and normal stress using the average strength values from Table 10 as data points. The cohesion value for concrete is defined as the value for the Y-intercept of the curve, and the angle of internal friction is defined as the value for the arctan of the slope of the curve. The cohesion and angle of internal friction for mixtures are present in Table 8. The stress-deformation curves are presented in Figures 7-12 for each of the normal stress conditions and mixtures.

Direct Tensile Strength

Twenty-two, 76-mm-diam by 152-mm-high cylindrical specimens were tested to determine the direct tensile strength (CRD C 164 (WES 1949b)) for the hardened concrete mixtures after curing. The results of these tests are presented in Table 11. Due to the high tensile strength of the RPC, many of the specimens experienced bond failure at the interface between the specimen

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Table 10
Direct Shear Strength for RPC Wet and Dry Mixtures

Mixture	Normal Stress at 0.4 MPa		Normal Stress at 0.8 MPa		Normal Stress at 1.6 MPa	
	Specimen	Strength MPa	Specimen	Strength MPa	Specimen	Strength MPa
Wet	970403-1	15.6	970403-2	11.9	970403-3	15.1
	970403-4	14.5	970403-5	11.9	970403-6	17.8
	970404-1	12.0	970404-2	15.8	970404-3	19.5
	970404-4	15.1	970404-5	14.1	970404-6	19.8
	Average	14.3	Average	13.4	Average	18.1
Dry	970443-1	11.5	970443-2	21.3	970443-3	11.5
	970457-1	21.5	970457-2	22.7	970457-3	25.2
	970458-1	13.8	970458-2	16.8	970458-3	16.8
	Average	15.6	Average	20.3	Average	17.8
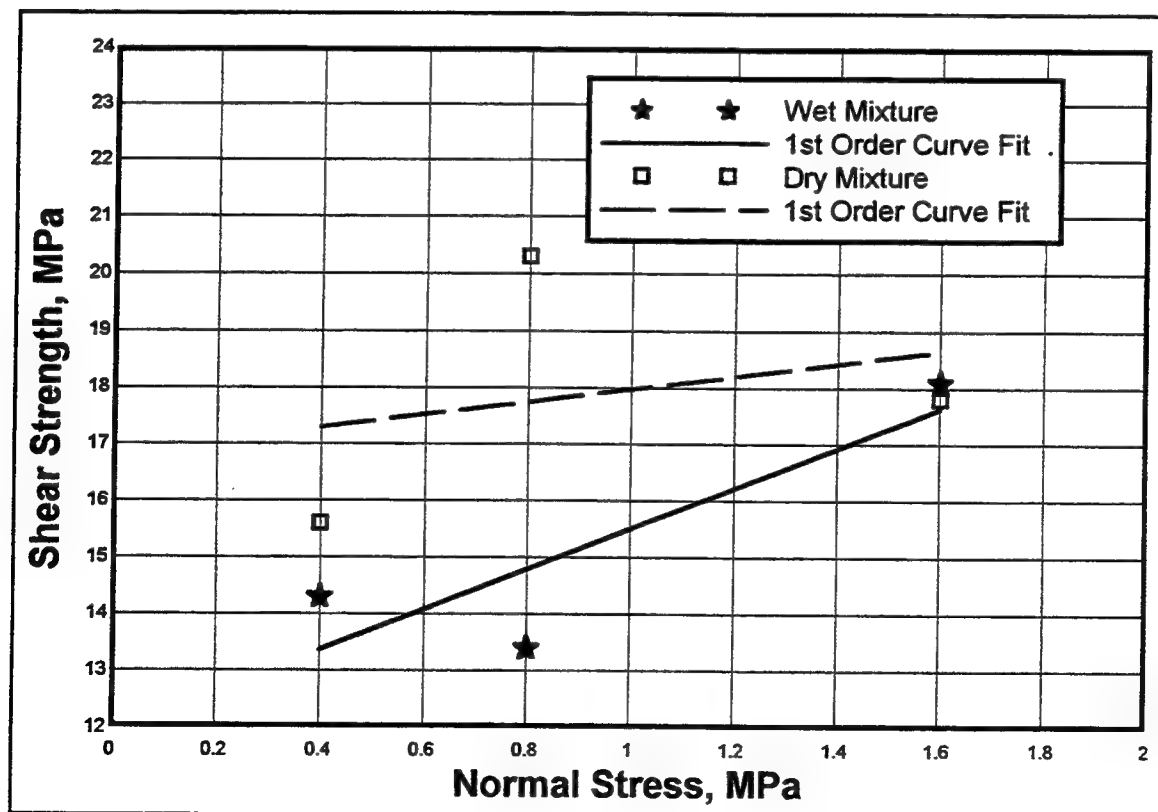
Figure 6.   Direct shear strengths for RPC wet and dry mixtures

Figure 7. Shear-strength test results for wet mixture at normal stress of 0.4 MPa

Figure 8. Shear-strength test results for dry mixture at normal stress of 0.4 MPa

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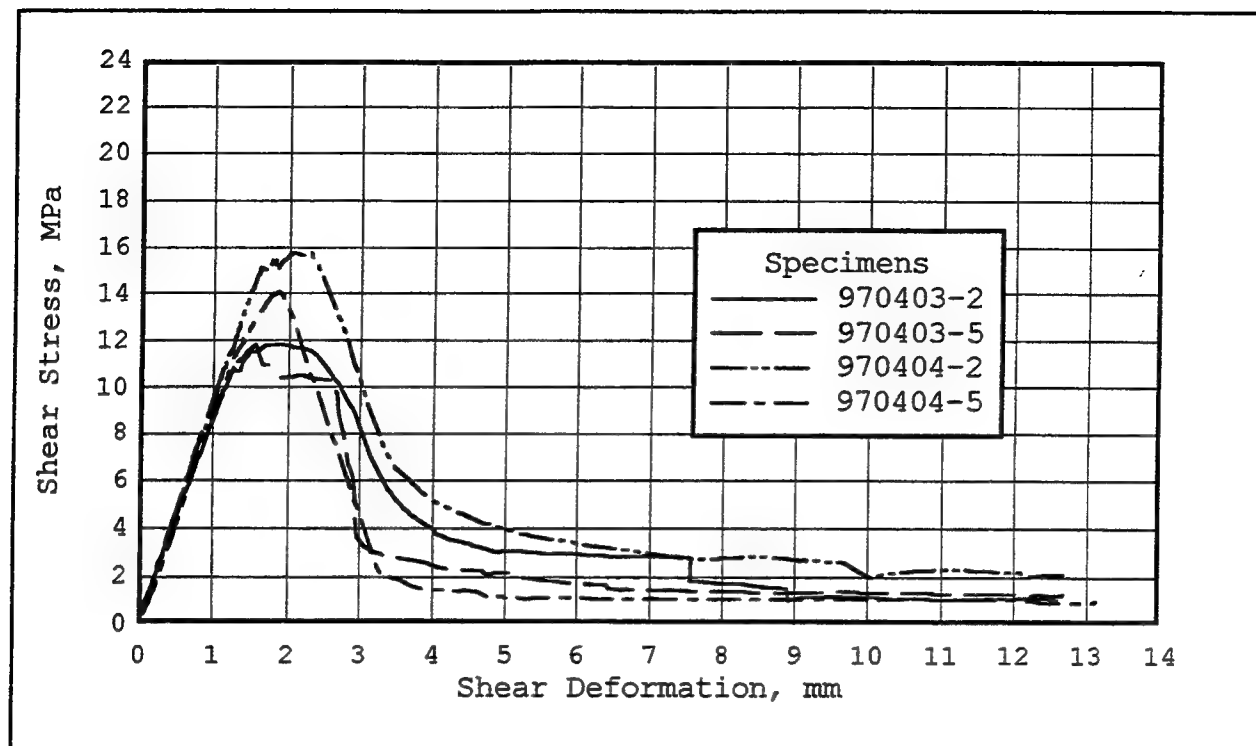
Figure 9. Shear-strength test results for wet mixture at normal stress of 0.8 MPa
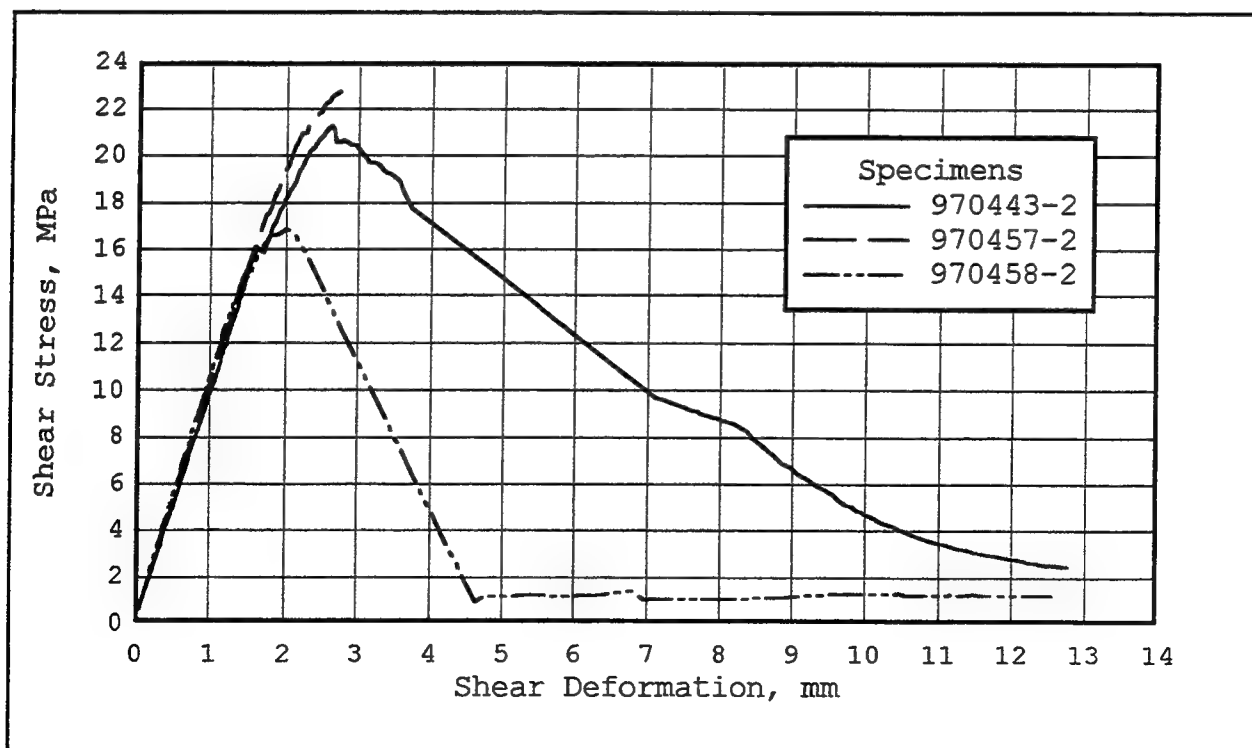
Figure 10. Shear-strength test results for dry mixture at normal stress of 0.8 MPa
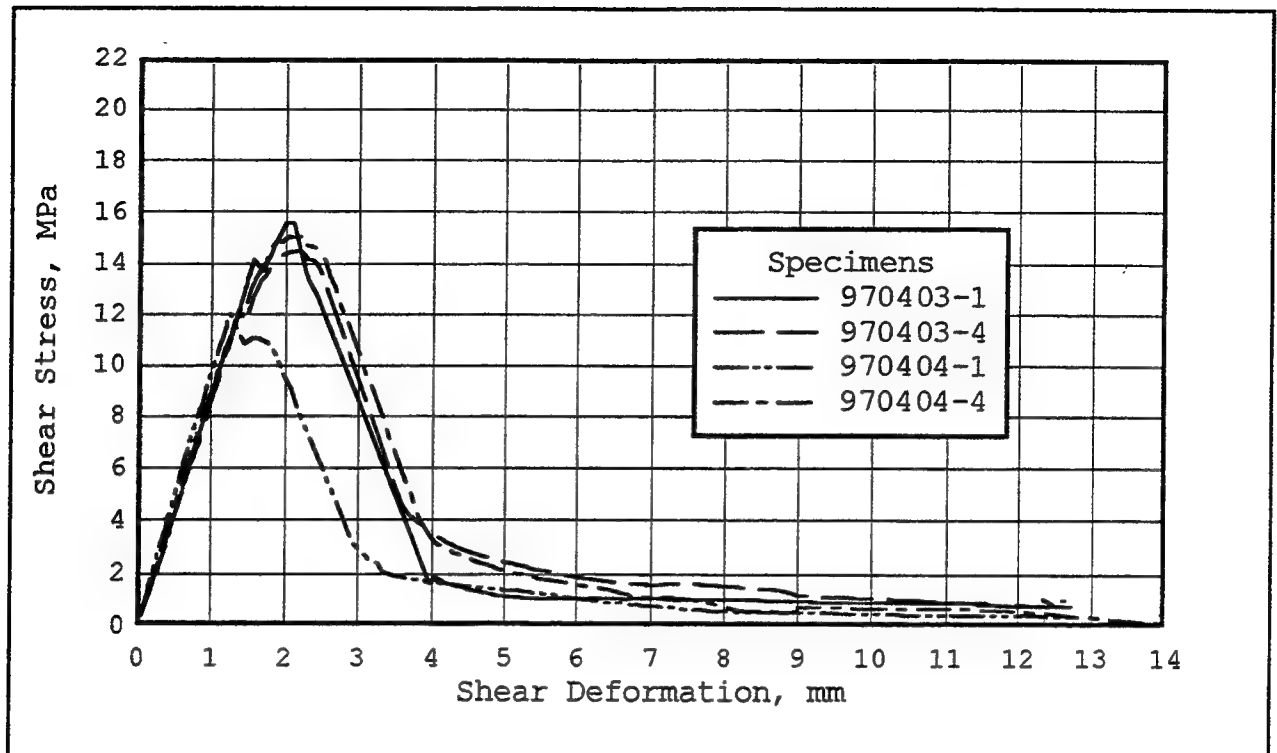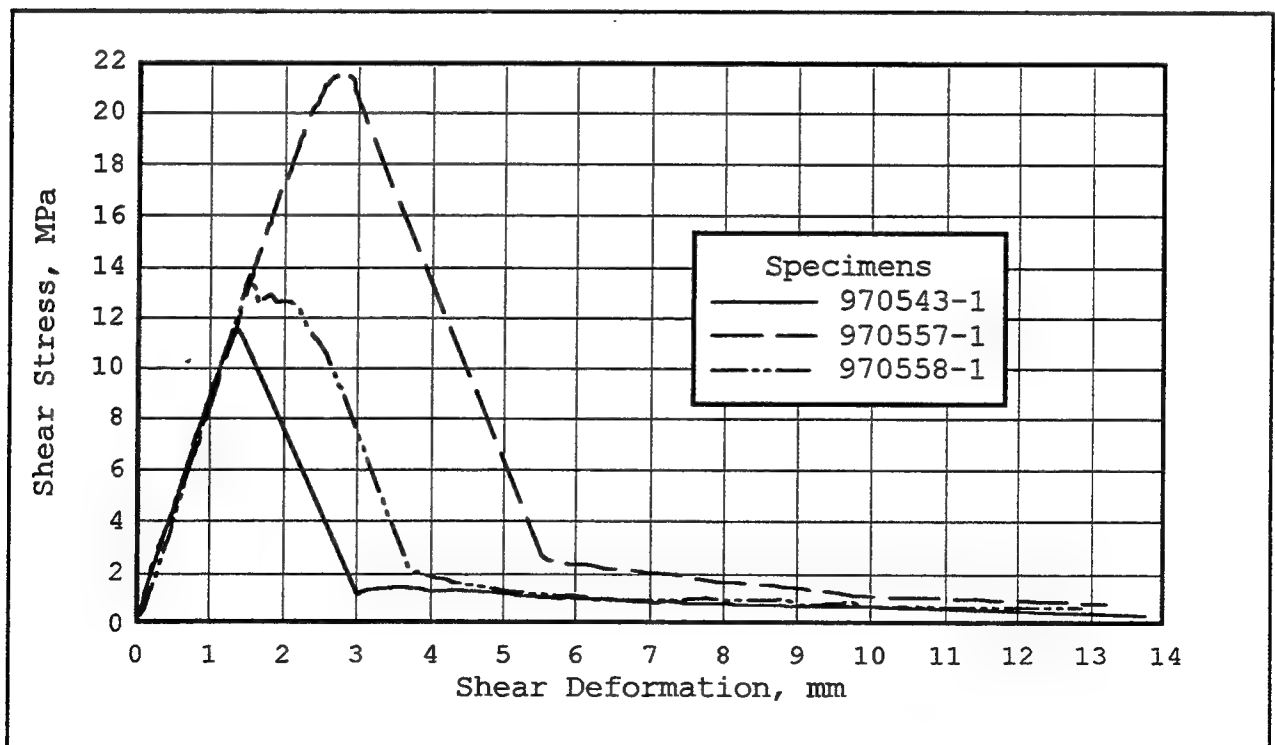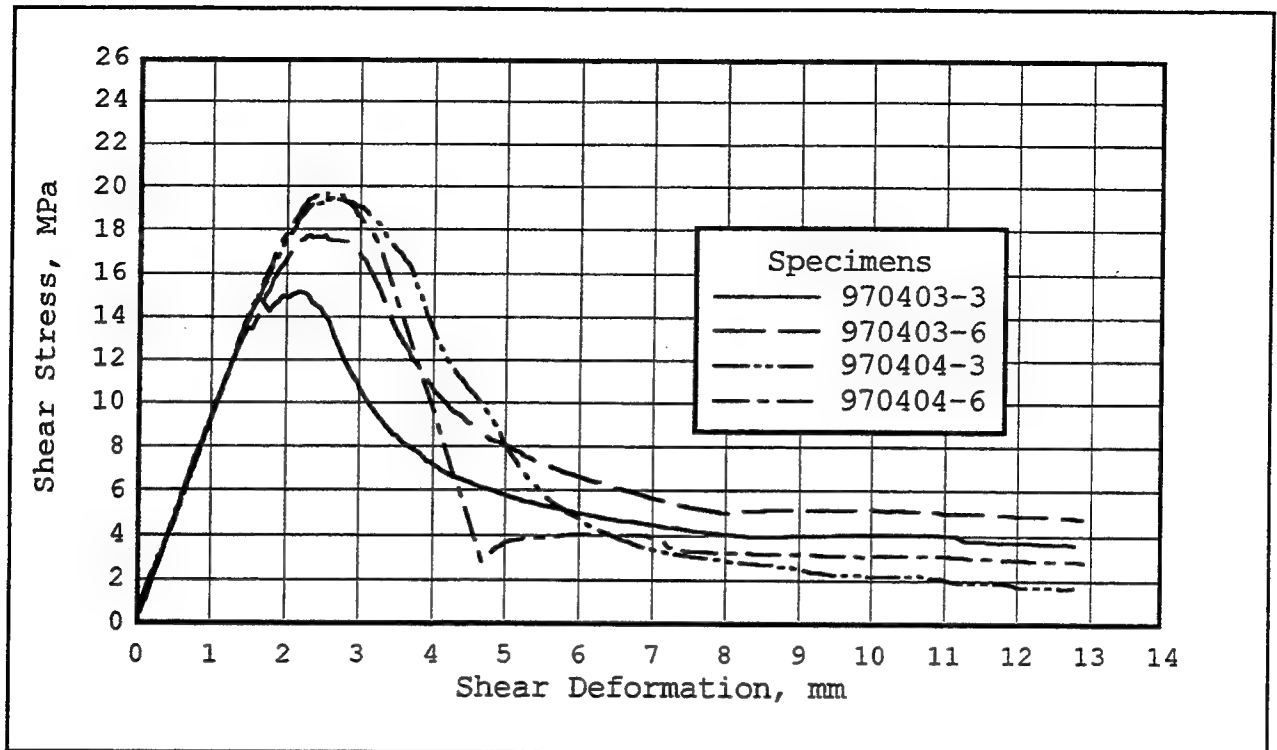
Figure 11. Shear-strength test results for wet mixture at normal stress of 1.6 MPa
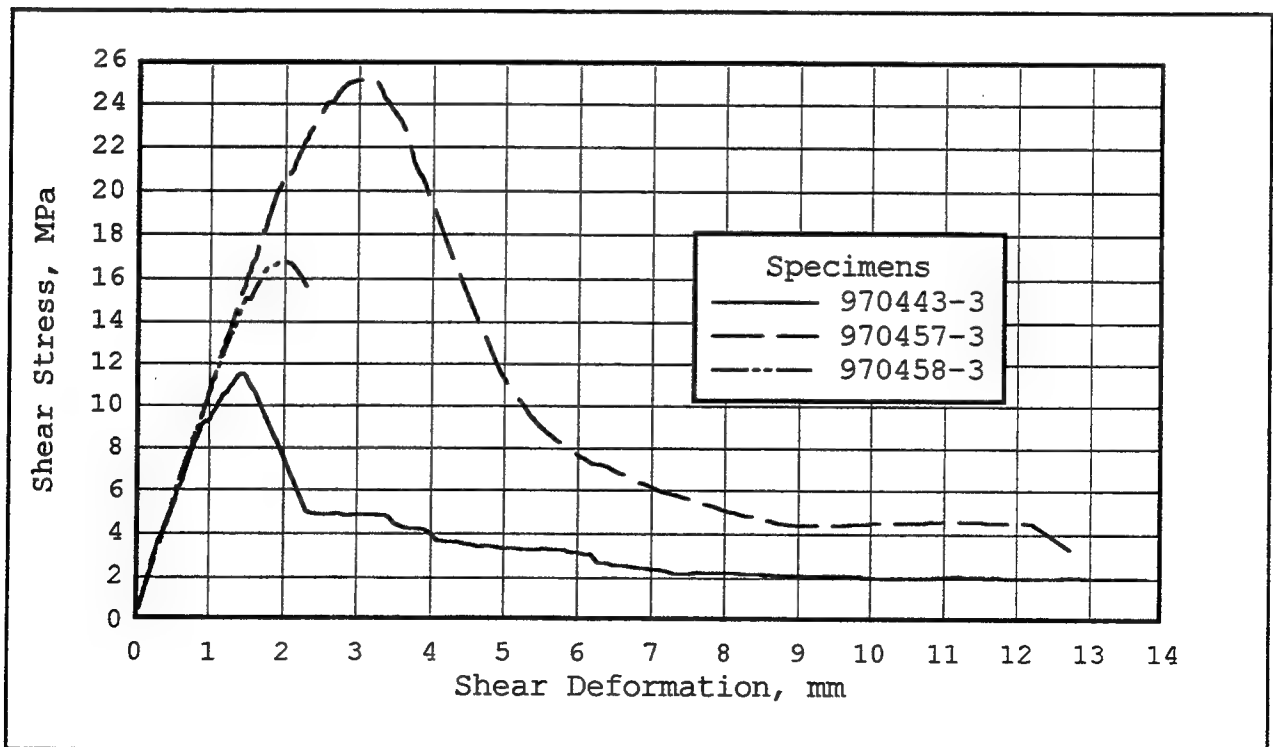
Figure 12. Shear-strength test results for dry mixture at normal stress of 1.6 MPa

Table 11
Direct Tensile Strength (CRD C 164[1]) for RPC Wet and Dry Mixtures

Wet Mixture			Dry Mixture		
	Tensile Strength			Tensile Strength	
Specimen	Failure	MPa	Specimen	Failure	MPa
970403-1	Interface	4.58	970443-1	Interface	6.40
970403-2	Interface	8.00	970443-3	Interface	8.25
970403-3	Interface	7.78	970443-4	Interface	6.76
970403-4	Interface	7.09	970443-5	Specimen	6.03
970403-5	Specimen	7.87	970457-1	Interface	9.20
970404-1	Specimen	8.35	970457-2	Specimen	10.51
970404-2	Interface	5.90	970457-3	Interface	5.60
970404-3	Interface	9.04	970457-4	Interface	4.30
970404-4	Interface	9.00	970458-1	Specimen	7.64
970404-5	Interface	6.03	970458-2	Specimen	8.96
–	--	–	970458-3	Specimen	6.94
–	–	–	970458-4	Specimen	9.40
Wet Mixture[2]	Interface	7.18	Dry Mixture[2]	Interface	6.75
	Specimen	8.11		Specimen	8.25
	All	7.36		All	7.50

[1] WES (1949b).
[2] Average strength.

and end cap. The tensile strengths reported in Table 8 were only for tests in which the failure plane was within the specimen. The average strengths are comparable with the 7-MPa direct tensile strength stated for RPC 200 in *VSL News* (1997).

Flexural and Fatigue Strengths

Eight 89 mm-wide by 114-mm-high by 406-mm-long beam specimens were tested to determine the flexural strength (ASTM C 78 (ASTM 1995b)) for the hardened concrete mixtures after curing. The results of these tests are presented in Table 12. The average flexural strengths are comparable with those developed by Bouygues (Table 1) and with the 40-MPa flexural strength stated for RPC 200 in *VSL News* (1997).

Forty-one 89-mm-wide by 114-mm-high by 406-mm-long beam specimens were tested to determine the flexural fatigue limit for the hardened concrete mixtures after curing. The test procedure was the same as specified in ASTM C 78 (ASTM 1995b) except the applied stress was a percentage of the ultimate and was cyclic.

Table 12		
Flexural Strengths (ASTM C 78) for RPC Wet and Dry Mixtures		
Mixture	Specimen	Modulus of Rupture, MPa
Wet	970403-1	41.7
	970403-2	32.1
	970404-1	46.9
	970404-2	38.6
	Average	39.8
Dry	970406-1	30.2
	970443-1	32.9
	970457-1	32.5
	970458-4	37.0
	Average	33.2
[1] ASTM (1995b).		

The results of these tests are presented in Table 13. Linear regression curve fits (Figure 13) are used to depict the relationship between modulus of rupture and number of cycles using the average number of cycles for each percentage of modulus reported in Table 12 as data points.

Resistance to Freezing and Thawing

Eight 89-mm-wide by 114-mm-high by 406-mm-long beam specimens were tested to determine the resistance to freezing and thawing (ASTM C 666, Procedure A (ASTM 1995i)) for the hardened concrete mixtures after curing. The durability factors and weight losses after 300 cycles of rapid freezing and thawing are presented in Table 14 for each of the specimens and mixtures.

Permeability

Two 76-mm-diam by 140-mm-high cylindrical core specimens were tested in Hassler cells to determine the permeability (CRD C 163 (WES 1949a)) for the hardened concrete mixtures after curing. No flows were observed through RPC specimens while testing at a confining pressure of 20.7 MPa and a drive pressure of 16.5 MPa. The resulting permeabilities for both wet and dry mixtures were 0 (zero) Darcy as reported in Table 8.

Resistance to Cavitation Erosion

Tests were conducted at the WES Cavitation Erosion Test Facility in which two RPC wet mixture specimens were evaluated for cavitation-erosion resistance. The upper portion of specimens included a 18-mm-high by

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Table 13
Fatigue Limits (ASTM C 78)[1] for RPC Wet and Dry Mixtures

	Wet Mixture				Dry Mixture		
Specimen	Percentage of Modulus of Rupture	Outer Fiber Stress MPa	Number of Loading Cycles	Specimen	Percentage of Modulus of Rupture	Outer Fiber Stress MPa	Number of Loading Cycles
970403-7	70	27.9	242,698	970457-3	65	21.5	38,028
970404-8	70	27.9	138,215	970406-2	60	19.9	209,000
970403-8	65	25.9	267,612	970443-3	60	19.9	122,352
970404-9	65	25.9	135,173	970443-4	55	18.2	1,297,452
970403-4	60	23.9	1,471,183	970457-4	55	18.2	17,230
970404-3	60	23.9	1,142,367	970443-2	50	16.6	2,000,000
970404-7	57	22.7	1,383,668	970457-2	50	16.6	2,000,000
970404-6	57	22.7	211,431	970458-2	50	16.6	965,655
970404-5	55	21.9	2,000,000	970406-3	50	16.6	500,535
970403-5	55	21.9	1,640,000	970457-5	47	15.6	2,000,000
970403-6	53	21.1	1,717,448	970458-5	47	15.6	2,000,000
970403-3	50	19.9	2,000,000	970458-6	47	15.6	2,000,000
970403-9	50	19.9	2,000,000	970443-5	47	15.6	2,000,000
970404-4	50	19.9	2,000,000	970458-4	47	15.6	2,000,000
970404-10	50	19.9	2,000,000	970443-6	46	15.2	2,000,000
970403-11	50	19.9	1,502,000	970443-7	46	15.2	2,000,000
970403-10	50	19.9	510,000	970457-6	46	15.2	2,000,000
970403-12	48	19.1	2,000,000	970457-7	46	15.2	2,000,000
970404-11	48	19.1	2,000,000	970406-5	45	14.9	2,000,000
970404-12	48	19.1	2,000,000	970458-3	45	14.9	2,000,000
--	--	--	--	970406-4	40	13.2	2,000,000

[1] Test same as specified in ASTM except applied stress was a percentage of the ultimate and was cyclic (ASTM 1995b).
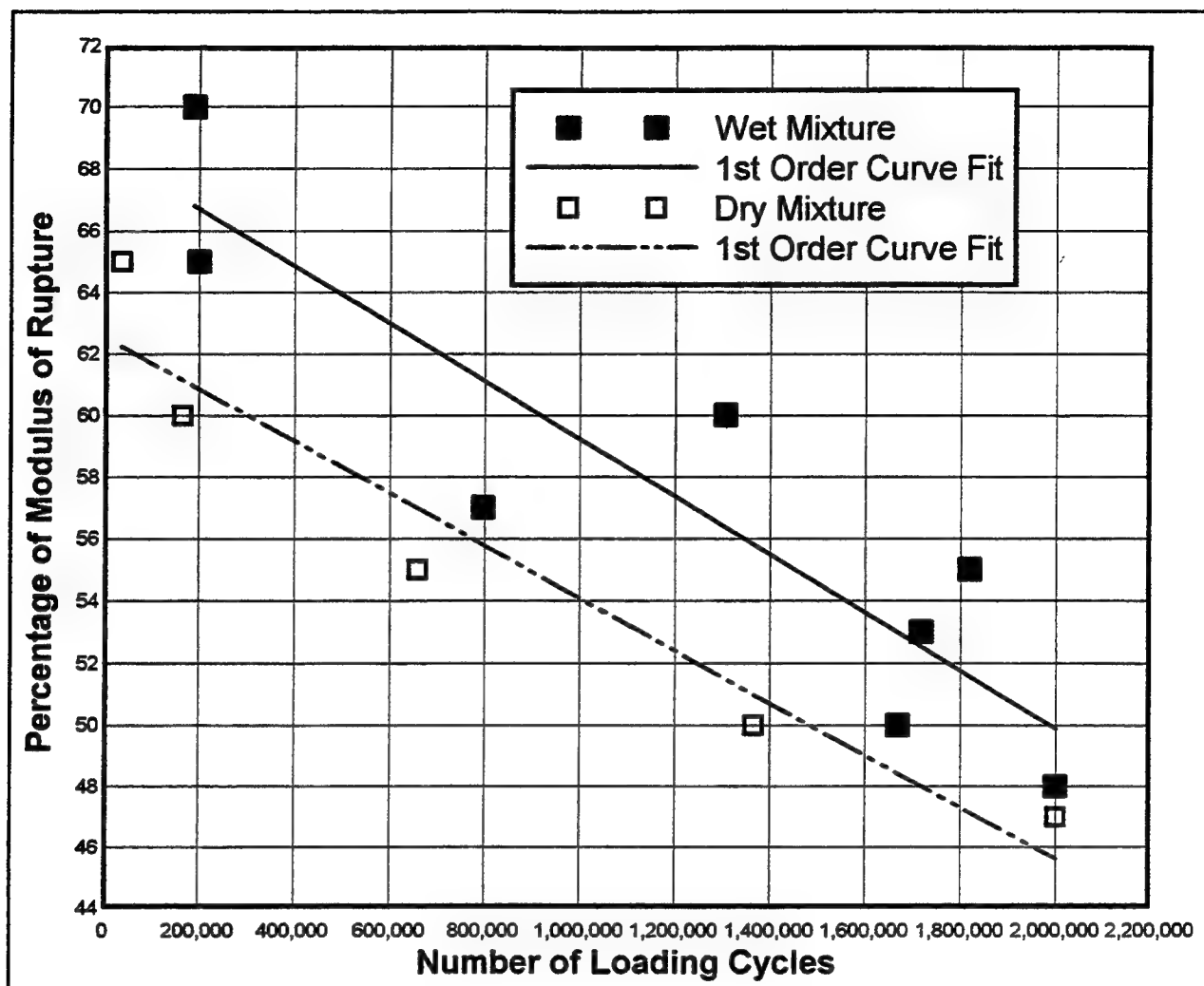
Figure 13. Fatigue limits for RPC wet and dry mixtures

Table 14							
Resistance of RPC to Rapid Freezing and Thawing							
(ASTM C 666, Procedure A[1])							
Wet Mixture				Dry Mixture			
Specimen	Relative Dynamic E-Modulus %	Durability Factor %	Weight Loss %	Specimen	Relative Dynamic E-Modulus %	Durability Factor %	Weight Loss %
970403-1	100.5	100.5	0.13	970406	99.5	99.5	0.29
970403-2	98.9	98.9	0.13	970443	100.0	100.0	0.17
970404-1	100.0	100.0	0.00	970457	99.0	99.0	0.17
970404-2	100.0	100.0	0.00	970458	100.6	100.6	0.22
Wet Mixture	99.9	99.9	0.07	Dry Mix	99.8	99.8	0.21
[1] ASTM (1995i).							

112-mm-wide by 122-mm-long test section. The volume losses from the test section were recorded at 2-hr intervals over an 8-hr exposure period. The average losses for the RPC and other concretes evaluated are presented in Table 15 and Figure 14. General background data for the mixtures are also furnished in Table 15.

Resistance to Sulfate Attack

Twelve 76-mm-wide by 76-mm-high by 254-mm-long bar specimens were cast using the RPC dry mixture proportions at a w/c of 0.19. Three bars were placed in water to provide control measurements. The other RPC bars were divided into groups of three with one group submerged in 2-percent sulfuric acid, another in a 10-percent sodium sulfate solution, and the last in a 10-percent magnesium sulfate solution.

Four other concrete pipe mixtures were also cast and placed using the same procedures and exposure conditions outlined for the RPC specimens. These mixtures included (a) a prestressed concrete mixture, (b) a prestressed concrete mixture containing a HRWRA, (c) a dry-cast mixture, and (d) a dry-cast mixture with 30-percent Class C Fly Ash replacement of the cement.

The mixture proportions for the two prestressed mixtures were selected by Gifford Hill America, Inc., in May 1994. The two dry-cast mixtures were designed by Cretex in April 1996. The prestressed mixture specimens were cast at WES, and the dry-cast mixture specimens were cast at Cretex and shipped to WES. The general mixture proportions for these four mixtures are presented in Table 16. The proportions for the RPC dry mixture are shown in Table 7.

The length change (ASTM C 157 (ASTM 1995d)) and loss of mass results for the five mixtures are presented in Tables 17-21. The length and mass changes are depicted in Figures 15-20 for each of the solutions.

Corrosion Protection

Three 152-mm-wide by 152-mm-high by 533-mm-long beam specimens containing 13-mm-diam steel reinforcement were cast using the RPC wet mixture. The reinforced beam specimens were identified as 960015, 960016, and 960017 and had concrete cover depths of 25, 19, and 10 mm, respectively. The specimens were cured in limewater for 28 days. In October 1996, specimens were shipped to Treat Island, ME, to study the effects of seawater on the corrosion of mild steel that was placed in RPC at different depths. After more than 2 years of exposure, the specimens were in good shape based on ultrasonic-pulse-velocity measurements (ASTM C 597 (ASTM 1995h)).

Table 15
Volume Loss Due to Cavitation Erosion

Mixture Description	Fine Aggregate	Coarse Aggregate	Water-Cement		Volume Loss (cc)				Rate cc/hr
			Ratio	Curing	2 hr	4 hr	6 hr	8 hr	
Silica-fume concrete	Bauxite	--	0.18	28 days in fog room	4.6	8.5	9.9	12.4	1.6
Silica-fume concrete containing steel fibers	Bauxite	--	0.18	28 days in fog room	5.9	9.4	12.0	14.8	1.9
RPC	Silica	--	0.17	[1]	6.2	10.7	12.6	15.5	1.9
Silica-fume concrete containing steel fibers	Natural	--	0.18	28 days in fog room	6.2	9.2	13.7	17.9	2.2
Silica-fume concrete	Natural	--	0.18	28 days in fog room	6.5	13.2	17.2	21.3	2.7
41.4-MPa, Type I portland-cement concrete	Natural	Natural	0.41	28 days in fog room	36.2	49.6	61.9	68.8	8.6
27.6-MPa, Type I portland-cement concrete containing deformed steel fibers	Natural	Natural	0.72	28 days in fog room	79.5	89.6	106.8	111.8	14.0
27.6-MPa, Type I portland-cement concrete containing straight steel fibers	Natural	Natural	0.72	28 days in fog room	88.4	104.3	132.6	134.0	16.8
27.6-MPa, Type I portland-cement concrete	Natural	Natural	0.72	28 days in fog room	44.8	62.1	101.4	--	16.9
27.6-MPa, Type I portland-cement concrete containing polypropylene fibers	Natural	Natural	0.72	28 days in fog room	68.8	91.9	115.9	139.4	17.4

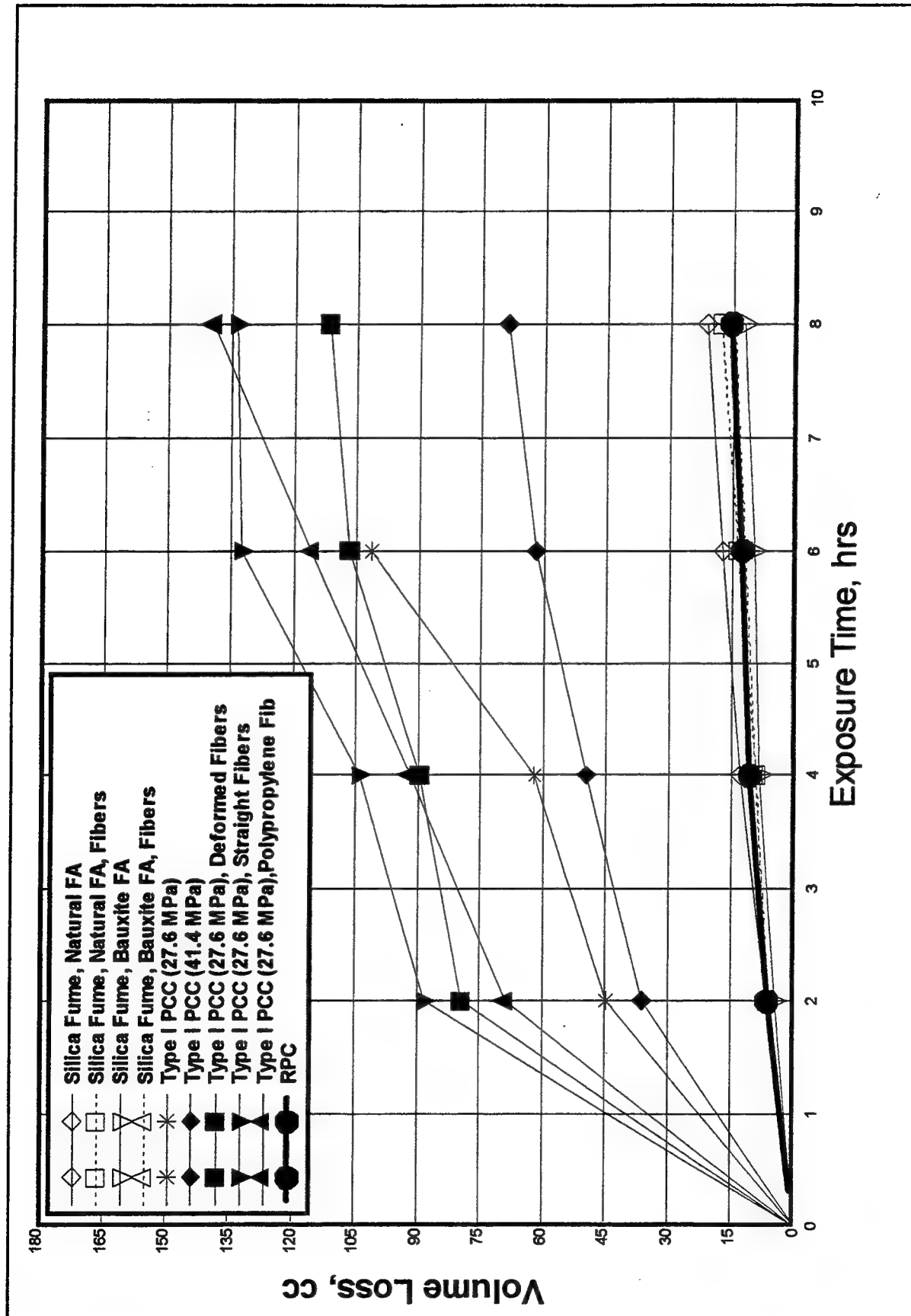[1] Thirteen days (7 days in limewater, 4 days in hot bath, and 2 days in hot air).

Figure 14. Volume loss due to cavitation erosion

Table 16
Proportions for Prestressed and Dry Cast Mixtures

Mixture	Material	Relative Mass	Mass per m^3 of Mixture, kg
GHA Prestressed	Type I Portland Cement	1.000	375
	Concrete Sand	2.488	932
	9-mm Chert Aggregate	2.681	1,004
	Water (w/c = 0.41)	0.409	153
GHA Prestressed with HRWRA	Type I Portland Cement	1.000	375
	Concrete Sand	2.488	932
	9-mm Chert Aggregate	2.681	1,004
	Water (w/c = 0.41)	0.409	153
	HRWRA (Pozzolith 80)	0.004	1.47
Cretex Dry Cast	Type I Portland Cement	1.000	381
	Concrete Sand	2.389	911
	Coarse Aggregate	2.658	1,014
	Water (w/c = 0.41)	0.408	155
Cretex Dry Cast with 30% Fly Ash	Type I Portland Cement	1.000	307
	Class C Fly Ash	0.427	131
	Concrete Sand	2.387	733
	Coarse Aggregate	3.794	1,165
	Water (w/c = 0.45)	0.452	139

Table 17
Changes in Length and Mass for RPC Dry Mixture Specimens Subjected to Sulfate Attack (CMD No. 960302, CAST 5-23-96)

Time day	Sulfuric Acid		Sodium Sulfate		Magnesium Sulfate	
	Expansion %	Loss of Mass %	Expansion %	Loss of Mass %	Expansion %	Loss of Mass %
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	-0.0219	-0.2595	-0.0010	-0.0327	-0.0003	-0.0452
14	-0.0229	-0.2401	0.0013	-0.0168	0.0003	-0.0523
21	-0.0215	-0.2984	-0.0013	-0.0064	-0.0007	-0.2291
28	-0.0215		-0.0013		-0.0007	
56	-0.0242	-0.5972	0.0000	-0.0103	0.0003	-0.3499
91	-0.0265	-0.6283	-0.0017	-0.0274	-0.0017	-0.3615
105	-0.0265	-0.6640	-0.0013	-0.0467	-0.0003	-0.3707
122	-0.0275	0.1074	-0.0027	-0.0454	-0.0017	-0.3531
182	-0.0292	2.4021	-0.0050	-0.0721	-0.0023	-0.3539
243	-0.0299	2.4804	-0.0050	-0.0709	-0.0037	-0.3414
365	-0.0498	8.0402	-0.0023	-0.0435	-0.0007	-0.2818
606	———	13.2789	-0.0053	-0.0246	-0.0033	-0.3914

Table 18
Changes in Length and Mass for Prestressed Mixture Specimens Subjected to Sulfate Attack (CMD No. 960301; Cast 5-21-96)

Time day	Sulfuric Acid		Sodium Sulfate		Magnesium Sulfate	
	Expansion %	Loss of Mass %	Expansion %	Loss of Mass %	Expansion %	Loss of Mass %
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	-0.0286	1.3558	-0.0007	-0.1564	-0.0007	-0.1943
14	-0.0349	2.9656	0.0027		0.0020	-0.2127
21	-0.0349	3.7186	0.0017	-0.1318	0.0017	-0.3187
28	-0.0395	4.3547	0.0000	-0.1391	0.0010	-0.3431
56	-0.0468	5.2350	-0.0030	-0.1777	-0.0010	-0.5554
91	-0.0478	5.4578	0.0007	-0.2194	0.0023	-0.5687
105	-0.0604	5.7333	0.0017	-0.2790	0.0030	-0.5830
122	-0.0604	5.9815	0.0017	-0.2902	0.0027	-0.6219
182	-0.1047	12.8981	-0.0017	-0.3999	0.0033	-0.7074
243	-0.1075	14.0892	-0.0006	-0.5324	0.0030	-0.8812
365	-0.1151	24.6510	0.0010	-0.6810	0.0030	-1.1755
606	-0.1125	33.0952	-0.0020	-0.5749	0.0020	-1.3062

Table 19
Changes in Length and Mass for Prestressed-HRWRA Mixture Specimens Subjected to Sulfate Attack (CMD No. 960305; CAST 6-4-96)

Time day	Sulfuric Acid		Sodium Sulfate		Magnesium Sulfate	
	Expansion %	Loss of Mass %	Expansion %	Loss of Mass %	Expansion %	Loss of Mass %
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	-0.0013	-0.6600	0.0003	0.0183	0.0007	-0.0426
14	-0.0017	-1.0908	-0.0023	0.0088	-0.0003	-0.1711
21	-0.0013		-0.0023		-0.0003	
28	-0.0003		-0.0013		0.0007	
56	0.0007	-0.0658	-0.0017	0.0010	0.0013	-0.6105
91	-0.0003	1.2321	-0.0030	-0.1046	-0.0007	-0.7826
105	-0.0003	1.5127	-0.0033	-0.1429	-0.0007	-0.8027
122	-0.0013	1.7068	-0.0040	-0.1661	-0.0017	-0.7802
182	-0.0073	9.2729	-0.0040	-0.3492	-0.0020	-0.9239
243	0.0017	10.2924	-0.0033	-0.6140	-0.0020	-1.2308
365	-0.0003	20.0142	-0.0017	-0.7695	-0.0013	-1.4659
606	-0.0013	29.2570	-0.0017	-0.9563	0.0000	-2.1098

Table 20
Changes in Length and Mass for Dry-Cast Mixture Specimens Subjected to Sulfate Attack (CMD No. 960303, CAST 6-10-96 and 6-11-96 (CRETEX))

Time day	Sulfuric Acid		Sodium Sulfate		Magnesium Sulfate	
	Expansion %	Loss of Mass %	Expansion %	Loss of Mass %	Expansion %	Loss of Mass %
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	-0.0043	2.1807	-0.0040	0.0056	-0.0040	-0.0791
14	0.0010	2.8465	0.0023	-0.0615	0.0010	-0.0925
21	-0.0017		-0.0003		-0.0020	
28	-0.0013	3.0398	0.0007	-0.0609	-0.0017	-0.0837
56	0.0013	3.1519	0.0000	-0.0954	0.0003	-0.2215
91	0.0020	3.2754	0.0003	-0.1030	0.0006	-0.4444
105	0.0020	3.4410	-0.0016	-0.1260	-0.0017	-0.5585
122	0.0030	3.8842	0.0013	-0.1204	0.0017	-0.6694
182	0.0040	3.9792	0.0023	-0.1335	0.0013	-0.6833
243	0.0070	4.2285	0.0033	-0.1401	0.0039	-0.7732
365	0.0083	10.1051	0.0053	-0.1477	0.0059	-0.8086
606	0.0076	10.6015	0.0070	-0.2349	0.0056	-0.0004

Table 21
Changes in Length and Mass for Dry-Cast, Fly-Ash Mixture Specimens Subjected to Sulfate Attack (CMD No. 960304, CAST 6-12-96 and 6-13-96 (CRETEX))

| Time day	Sulfuric Acid		Sodium Sulfate		Magnesium Sulfate	
	Expansion %	Loss of Mass %	Expansion %	Loss of Mass %	Expansion %	Loss of Mass %
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	-0.0017	-1.1286	0.0000	-0.0061	-0.0003	-0.0222
14	0.0020	0.1588	0.0013	-0.0274	0.0017	-0.0663
21	0.0017		0.0007		0.0003	
28	0.0017	0.7482	0.0007	0.0193	0.0003	-0.0836
56	0.0033	1.8050	0.0003	0.0363	0.0017	-0.2854
91	0.0036	1.8548	0.0010	0.0338	0.0023	-0.4168
105	0.0070	1.9502	0.0020	0.0288	0.0040	-0.5491
122	0.0060	1.9582	0.0027	0.0210	0.0070	-0.6450
182	0.0089	2.2350	0.0043	0.0328	0.0073	-0.6449
243	0.0103	2.4872	0.0043	0.0662	0.0106	-0.7889
365	0.0109	5.6991	0.0053	0.0629	0.0123	-1.0361
606	0.0109	8.0596	0.0026	0.0458	0.0109	-0.1374
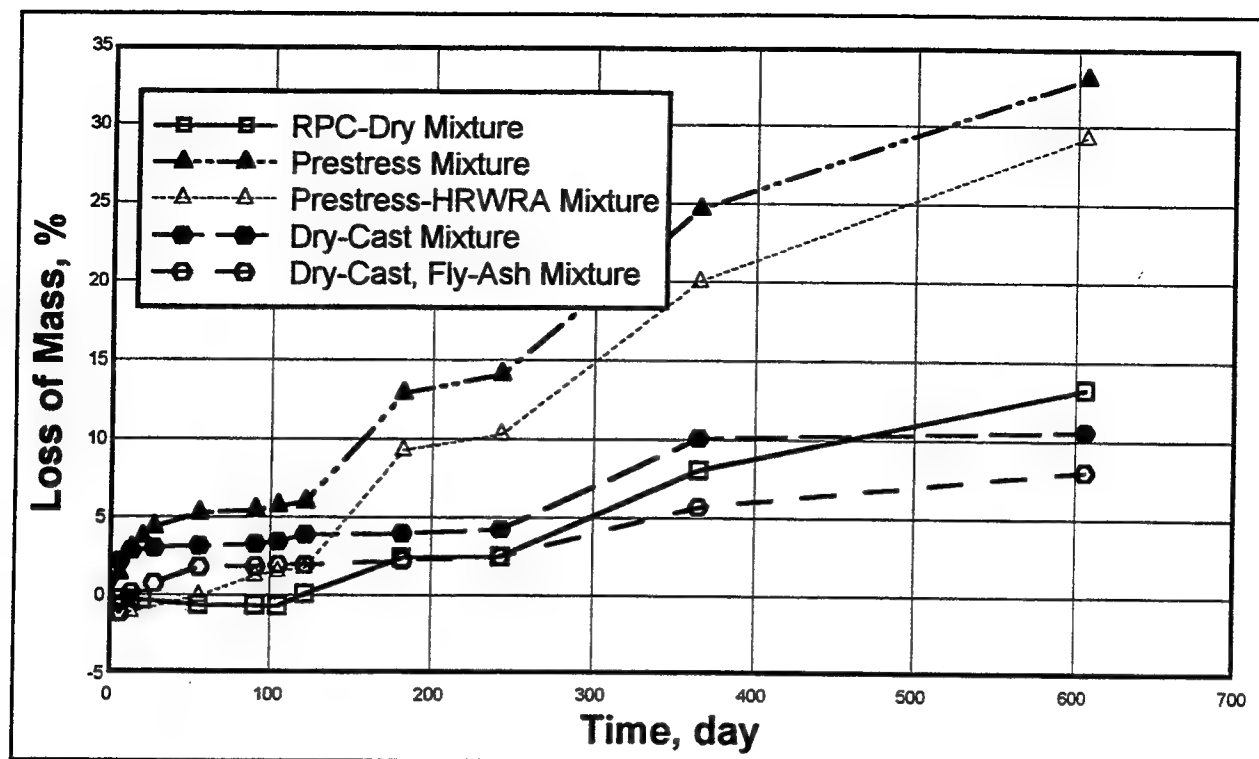
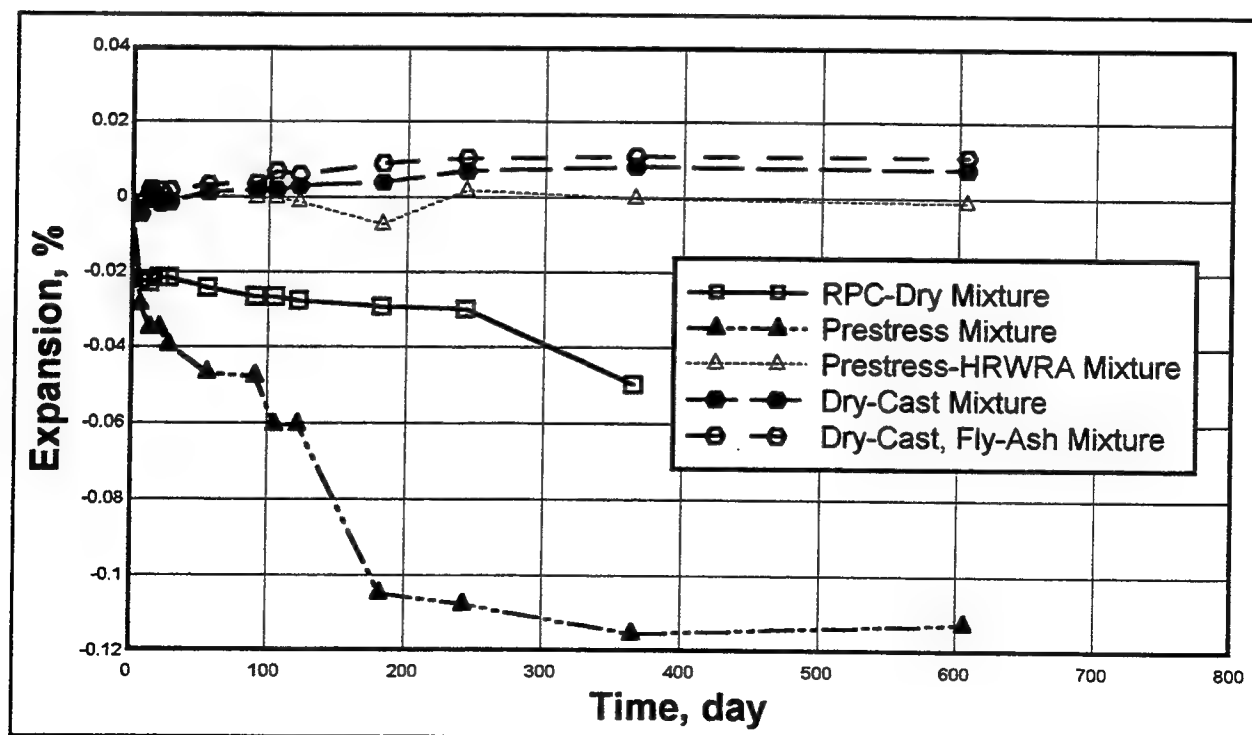Figure 15. Loss of mass for specimens in 2-percent sulfuric acid

Figure 16. Length changes for specimens in a 2-percent sulfuric acid
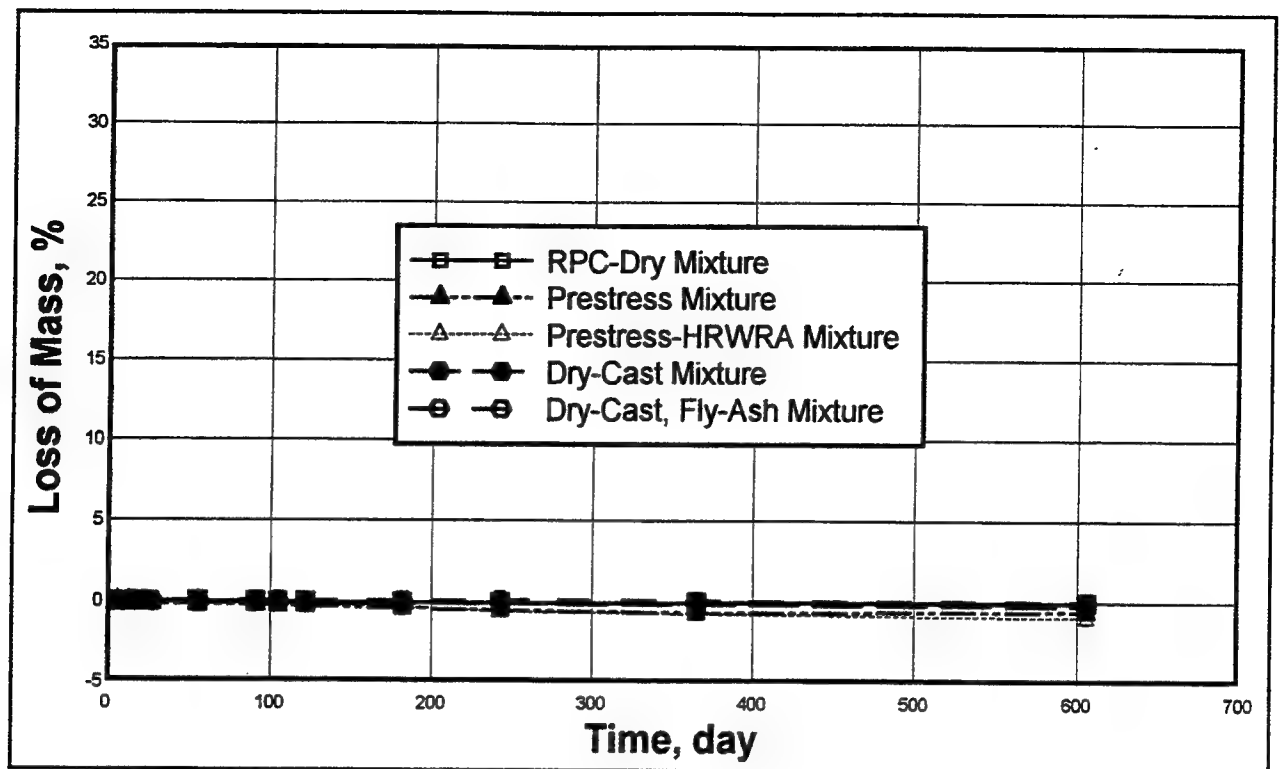
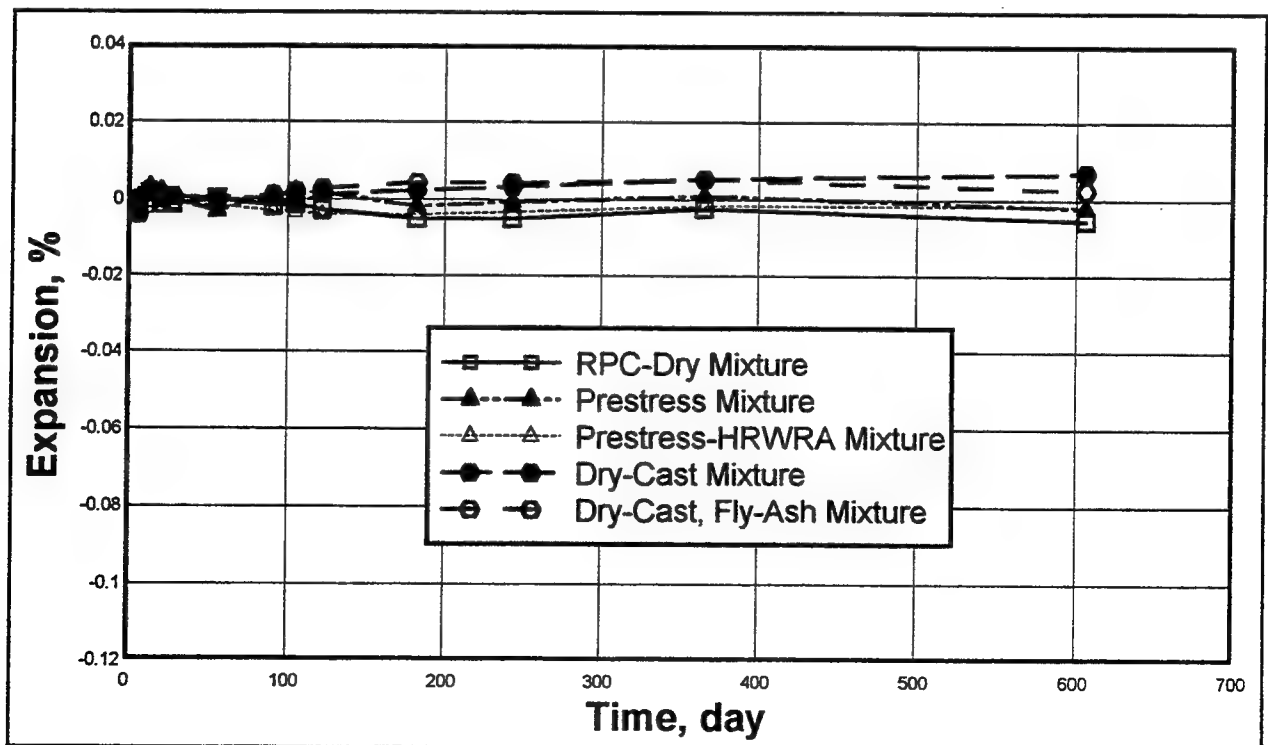Figure 17. Loss of mass for specimens in a 10-percent sodium sulfate solution

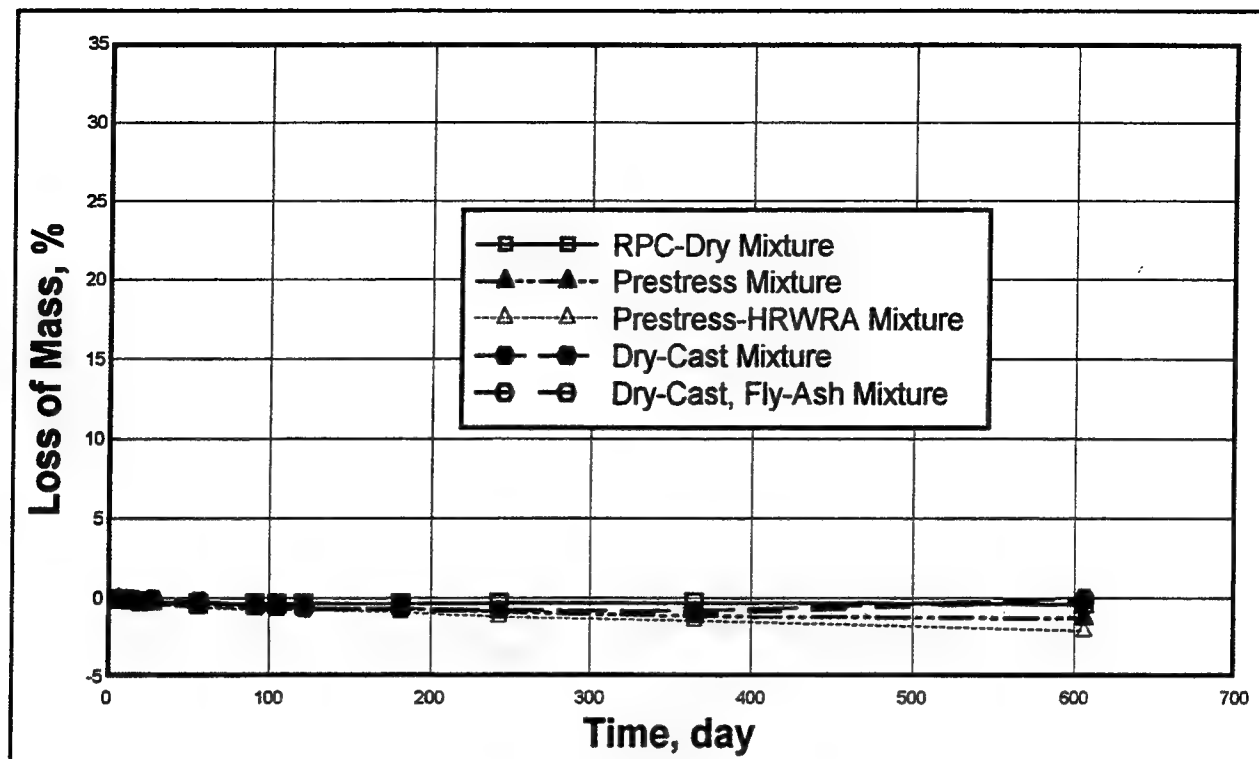Figure 18. Length changes for specimens in a 10-percent sodium sulfate solution

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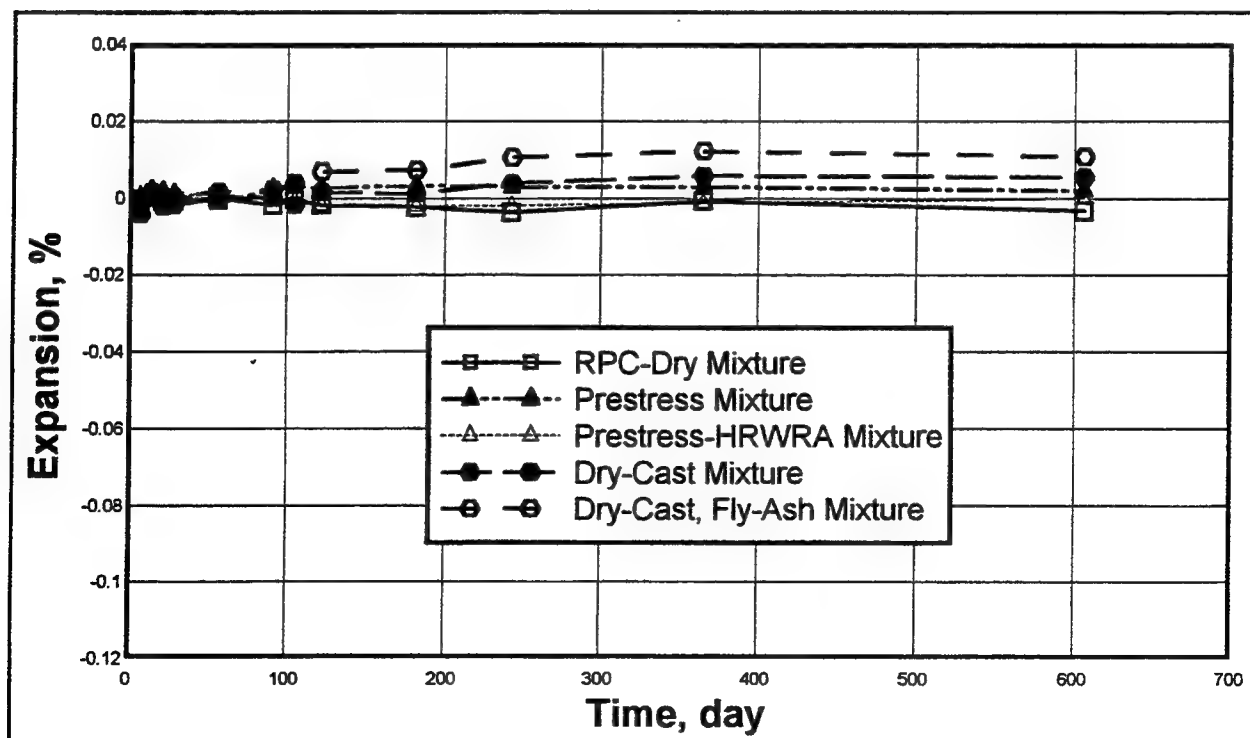Figure 19. Loss of mass for specimens in a 10-percent magnesium sulfate solution

Figure 20. Length changes for specimens in a 10-percent magnesium sulfate solution

4   Prototypes

Production Methods

Sewer/culvert and pressure pipes, two major areas of precast pipe production, were investigated as a part of this research. Both classes have distinct and different production processes that affect the proportioning of the RPC.

In developing the prototype design for precast RPC pipes, a comprehensive list of goals that make use of the enhanced properties of RPC was developed. These included:

- Production of lightweight units.
  - Reduced shipping and handling costs.
  - Reduced damage during handling and placing.
  - Reduced installation time.

- More efficient structural design resulting from the use of flexible pipe theory.

- Improved joint details and watertightness.

- Improved resistance to attack by sulfates and other chemicals.

Through optimization of the design of RPC pipes, it was projected that each of the above goals could be achieved.

Sewer/culvert pipe

Precast concrete pipes are commonly used for several gravity-flow piping applications such as drainage culverts, storm sewer systems, and sanitary sewer systems. The pipe design for these applications is generally controlled by the loading from the surrounding soil and surcharge from surface live loads. Watertight joints are generally required for sanitary sewer systems, whereas lower cost joints may be specified for culvert installations.

The two main methods used in producing culvert and sewer pipes are the dry-cast and the packer-head. The forming system for the dry-cast method is similar to that used for wet casting. The major difference in the two methods

is the consistency of the mixture that is used and the time period between casting and demolding.

Dry-cast method. In wet casting, a mixture with a slump of approximately 100 mm is used, whereas a zero-slump mixture is used with dry casting. Wet-cast forms are stripped 1 or 2 days after casting, but with dry-cast pipes, both the inner and outer forms are stripped immediately after casting. The aggregate interlock resulting after intense vibration coupled with the wire mesh used to reinforce the pipes provides the stability necessary for immediate demolding of dry-cast pipes.

The basic formulation of RPC had to be modified for it to be usable in the dry-cast method. Due to the necessity for the freshly cast concrete to support its own mass immediately after casting, the RPC had to be formulated to have a zero slump. This presented a challenge since RPC is generally very fluid.

To provide a zero slump, a portion of the cement was replaced with silica flour (30 percent by weight of cement), and the water-binder ratio was reduced to 0.13. The silica flour was added to introduce non-plastic particles in the size range of the cement to build the granular structure needed to support the pipe at early age.

One adverse condition existed at this point in the development of RPC pipe cast using the dry-cast method. The nature of RPC at the extremely low water-to-binder ratios used for dry-cast pipe made the material very cohesive and, under some circumstances, difficult to remove from the formwork when it was only minutes old. Research was conducted to identify form-release agents that were effective in reducing this cohesiveness and improving the form-release process. These are presented in Figure 21.

Packer-head method. The packer-head method, used extensively for gravity-flow pipes with diameters of 1,200 mm and smaller, is a heavily automated process. A stationary external pipe form is positioned in the mechanized casting bed, centered over an internal core mechanism that will rise up from beneath the bottom of this form for casting the pipe section (Photo 1). A rotating distributing head is situated on top of the core mechanism that is designed to propel the concrete mixture onto the outer form. Directly below the distributing head are rollers that pack the plastic concrete against the outer form. Below the rollers is a vibrating steel inner form that produces the finished interior surface of the pipe. After casting, an overhead crane lifts the newly cast pipe and the outer form off the casting bed and transports them to the stripping area. The exterior form is then removed, and the pipe is rolled into a curing chamber.

When the use of RPC with the packer-head method is considered, the issue of stability after demolding presents a challenge. However, it appears quite practical to use a very stiff mixture without adversely affecting the casting operation. Since there is intense working of the plastic mixture against the outer form, a dense, well-compacted, and stable pipe product appears attainable with a stiff RPC mixture. Furthermore, the entrapment of air is not viewed to be a concern with this method.
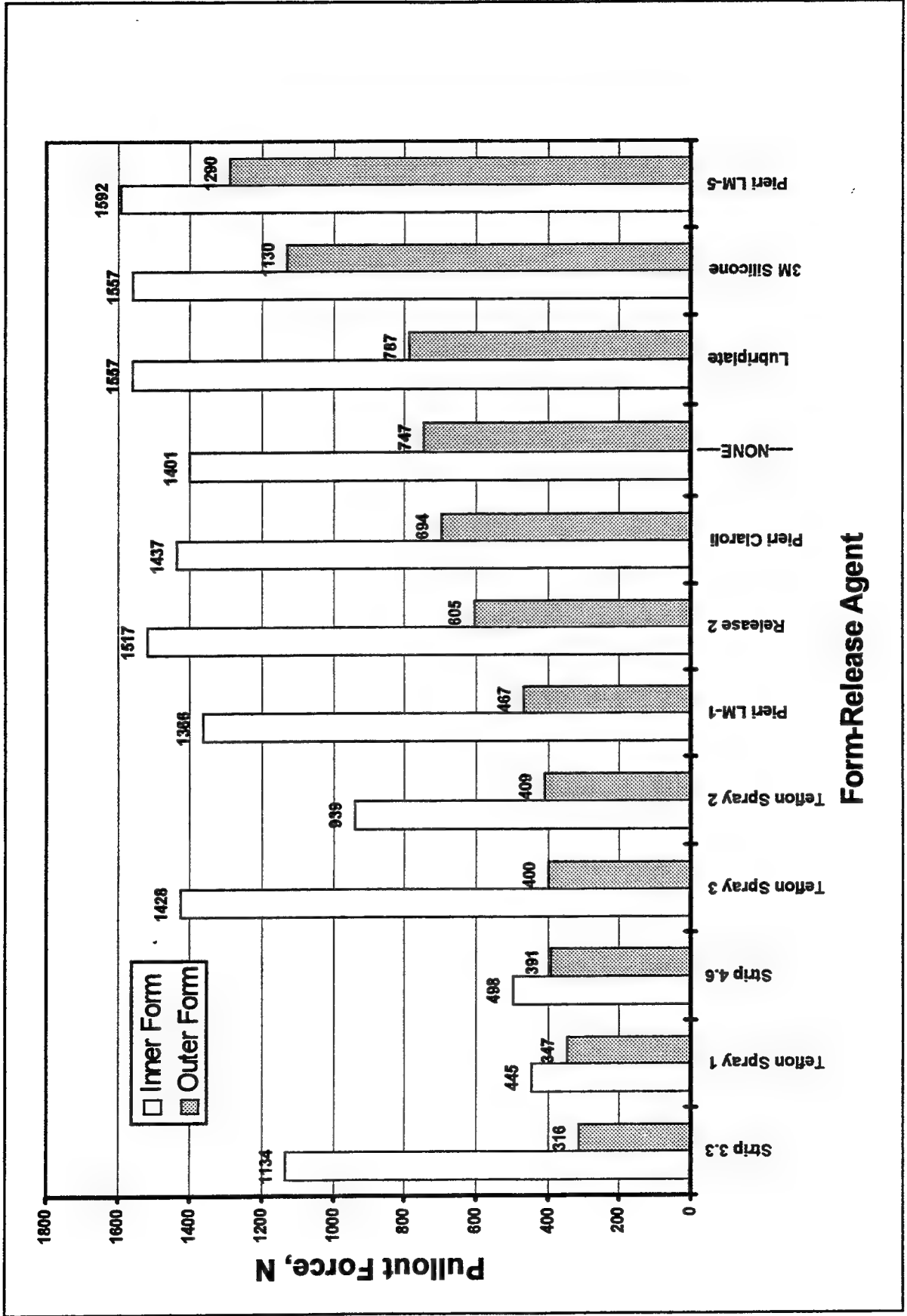
Figure 21. Pullout forces required to release inner and outer forms from RPC specimen

Pressure pipe

Pressure pipes are subjected to internal pressure from hydraulic pumping heads. Since these pipes are under internal pressure, the direct tensile capacity of the concrete is a factor. Internal pressure causes hoop stresses in the wall of the pipe, and thrust forces encountered in pipe bends and elbows produce longitudinal tensile forces. The high tensile strength of RPC is a distinct advantage in designing for pressure pipe.

Current concrete pressure-pipe technology requires a multiple step fabrication process for pipes where liquid containment is a necessity. For pressure pipes requiring watertightness, the process begins with the fabrication of a thin-wall steel pipe or cylinder which provides the watertightness. A concrete core is spun-cast to the interior of the steel pipe to provide structure for the pressure pipe and to protect the interior of the steel from corrosion. The steel cylinder is then tightly confined by winding prestressing wire around the exterior of the cylinder. The prestressing restrains any movement of the concrete and steel cylinder due to the high internal pressures. To protect the exterior from corrosion, a shotcrete coating of mortar is applied over the prestressing and steel cylinder.

For high-pressure pipe applications using RPC, the core will still need to be prestressed to resist the internal hoop stresses from the fluid pressure. However, the compressive strength of RPC is significantly higher than that of conventional high-strength concrete and will be able to resist the compressive stresses imposed by the steel prestressing wire without the need of the steel cylinder.

For lower pressure applications, the potential exists to use RPC without the prestressing. It is anticipated that operating tensile hoop stresses of up to 10 MPa may be accommodated by RPC pipe without the prestressing steel. With the successful development of such a pipe, a significant reduction in the production cost of pressure pipe would result. Pipes could be fabricated in a single casting operation, thus simplifying the multiple-step process of conventional pressure pipe. Additional savings in material costs will result from the elimination of the costly steel cylinders and prestressing wire. This research also investigated the possibility of fabricating RPC joint rings integrally with the pipe-casting operation. This will further reduce the cost and simplify fabrication.

Wet-cast method. The wet-cast method involves the use of inner and outer pipe forms positioned on a baseplate. A casting cone is generally placed on the top of the inner form to funnel the concrete into the annular space between the inner and outer forms. External vibration is traditionally used to consolidate the concrete. After the concrete has set and the formwork has been removed, prestressing wire is wound around these pipes to provide the containment for the high pressures, and a mortar coating is provided over the prestressing to protect it from corrosion.

In the wet-cast method, concrete is often dropped large distances, which can entrap air in the mixture. Since RPC is intentionally formulated to minimize any internal voids, this condition is detrimental. Because of this phenomenon,

it is advantageous to cast RPC with a method that minimizes the entrapment of air. Since a high-quality RPC mixture can be achieved with a very fluid consistency, an injection casting method was developed. With this method, the RPC mixture is pressure pumped through a closed piping system into the bottom of the form, filling the form from the bottom up. This method should not only minimize the entrapment of air but also can potentially reduce the overall labor cost needed to cast the pipe.

To date, RPC has been placed using the wet-cast method at three different production plants in the United States. Each of these trial castings has resulted in the production of a high-quality prototype. An RPC mixture proportion with a relatively fluid consistency was used for each casting.

Spun-cast method. The spun-cast technique for high-pressure pipe is well suited to the use of RPC. This method is generally used in the production of pressure pipes having a diameter of 1,200 mm and smaller. The method involves the placement of a precise amount of concrete mixture into an exterior pipe form positioned horizontally in a bed designed to spin the pipe form on its longitudinal axis (Photos 2-3). With conventional concrete pressure pipe, the steel cylinder also serves as the rotating pipe form. As the form spins, the centrifugal force distributes the concrete evenly along its length and perimeter. The forms are rotated at 200 to 500 rpm for approximately 10 min. Upon completion of the spinning, the forms are removed from the spun-cast facility and allowed to cure.

Spin casting of conventional concrete mixtures normally results in some segregation of concrete components, a condition that can sometimes be a problem. The centrifugal force of spin casting drives the aggregate to the outside near the form, and a significant amount of water and cement are forced to the free surface at the interior of the pipe. This results in a deposit of a laitance of weak, high-water-content paste on the inside surface of the pipe. This laitance deposit and the concrete segregation reduce the quality of the concrete pipe products. When RPC was used in this spun-cast process, no segregation of materials was observed, and only a very thin laitance layer was detected on the interior surface of the pipe.

Some fiber migration was observed in small-scale spun-cast trial mixtures of RPC specimens. This phenomenon was generally associated with mixtures that had higher fluidity and only when the rotational velocities were at the upper end of the production range.

Fabrication and Testing

The relative masses for the RPC mixtures used to cast prototype specimens were the same as those for the wet and dry mixtures used to determine physical properties (Table 7), except the water content was adjusted to change the rheology of the mixtures.

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Gifford Hill American, Inc.

Prototype pressure pipes were cast on December 9, 1995, at the Gifford Hill American, Inc., production plant in Grand Prairie, TX. The purpose of this trial was to determine which industrial process would be the most adequate for RPC pressure-pipe production and to apprehend RPC material on a production scale.

Four vertical prototype pipe specimens were fabricated using the wet-cast method, and two other pipe specimens were fabricated using the spun-cast method. Two of the wet-cast pipes had a diameter of 1,220 mm, a wall thickness of 38 mm, and a height of 2.45 m. The other two wet-cast pipes had a diameter of 1,370 mm, a wall thickness of 44 mm, and a length of 2.45 m. For the two spun-cast pipes, one had a diameter of 760 mm, a wall thickness of 25 mm, and a length of 4.90 m, and the other had a diameter of 610 mm, a wall thickness of 19 mm, and a length of 4.90 m.

The RPC wet mixture was used to cast both the wet-cast and spun-cast specimens. Observations and other details regarding the batching operations are presented in Table 23. Cylinders were cast and tested in compression by Gifford Hill. The compressive strengths for batches 2, 3, and 4 were 159, 158, and 155 MPa, respectively. All RPC batches were mixed in a semi-open room at a temperature around $0°$ C using a 1.9-m^3 pan mixer.

The wet-cast pipes were placed in two lifts using batch 2 for the first lift and batch 3 for the second. The RPC mixture was placed using a conventional concrete bucket. External form vibration was used. The casting operation began approximately 5 min after the end of mixing. During casting, a few bubbles were popping up on the exposed surface of the pipes, and a shiny-looking, thin film of water was present. No sign of major leak or bleeding of the formwork was observed.

Prior to prototype batching and casting, spun-cast cylinders were cast in the Gifford Hill laboratory to fine-tune the w/c for spin casting. A total segregation of fibers was observed on the outside of the cylinder wall for a w/c of 0.19 (Dauriac 1995b). The fibers were concentrated in the outer one-third of the wall thickness. The distribution of fibers was slightly improved by lowering the w/c. A lower speed for the centrifuge would prevent the segregation, but would induce an undesirable rough surface for the inside wall. Gifford Hill representatives selected a w/c of 0.16 for the spun-cast prototype mixtures.

Spun-cast pipes were cast with batch 4. RPC was placed from a special concrete bucket with a narrow trap at the bottom into a delivery tongue device (Photos 2-3). Several passes back and forth were necessary to fill this tongue. It took approximately 2 min to complete this operation. Some vibration was required to deliver the RPC. Casting of the first pipe began a half an hour after the end of mixing. Only half of the batch was used; the other half stayed in the mixer. Afterwards, the RPC was remixed for 1 min. The casting of the second pipe began an hour and a half after the end of the first mixing.

The pipe form was spinning at a low speed as the RPC was dumped from the tongue into the formwork. At first, the material was unequally distributed, causing the casting to be out-of-balance. After approximately 5 min, the speed of the casting was gradually increased to the maximum of 419 rpm (770-m/sec^2 acceleration) for the 760-mm-diam pipe and 751 rpm (1,780-m/sec^2 acceleration) for the 610-mm-diam pipe. At this point, the spinning process went fine.

After the spinning, the RPC was still resilient but stuck to the form. A lot of laitance was observed on the inside surface of the pipe. The surface had a smooth finish with no segregation of fibers observed. No demarcation line was observed either at the dumping point or the joining point of the fresh material. The distribution of the material along the circumference of the pipe was very homogeneous.

All pipe specimens were covered without applying a curing compound. Within an hour, specimens were moved inside to an insulated and heated building. Steam was applied for 2 days underneath the forms to maintain the temperature above freezing. Specimens were then steam-cured for 1 day at 70° C. The steam was applied directly to the outside form of the spun-cast pipes and to the inside core of the wet-cast pipes. Forms were stripped 3 days after casting.

Major longitudinal cracks inside and outside for both kinds of casting were observed (Dauriac 1995b). Some of these cracks were hair-line, while others were wide enough to allow light to go through (5 mm). Most of these cracks ran from one end of the pipe to the other. Because of the crack pattern, it was believed that testing of prototypes should be aborted because the results would be nonrepresentative.

As a result of this trial, it was demonstrated that RPC could be mixed in a production-size mixer at a low w/c (0.16) and successfully cast as prototype pipes using both the wet-cast and spun-cast industrial processes. One of the problems that must be remedied for a viable RPC spun-cast production is the slow delivery of RPC into the tongue delivery system. To combat potential cracking due to loss of moisture during steam-curing, it was suggested that forms be unlocked or removed and that steam be applied directly in contact with the RPC.

In 1996, two vertical prototype pipes were fabricated by pumping RPC through ports located at the bottom of the forms. The first specimen had a single port, and the second specimen had two ports on opposite sides of the form. After the first was demolded, it was observed that a seam had formed on the opposite side of the pipe at the junction where the two tributaries of RPC had flowed around the inner core and met. It was also observed that the second specimen had two seams, one on each side of the pipe at the midpoint between ports. It was later determined that the pumping process had caused a general orientation of the fibers in the direction of the axis of the pipe. The orientation of the fibers combined with the observed seams reduced the hoop-stress capacity of the pipe.

International Pipe Machinery Corporation

Prototype pipes were fabricated using the dry-cast method on December 18, 1995, at the International Pipe Machinery Corp. facility in Sioux City, IA. The purpose of this trial was to determine if RPC was viable for dry-cast technology where immediate demolding of prototype pipe specimens was employed and for the representatives from the Nebraska Concrete Pipe Association to apprehend the RPC material on a production scale.

The RPC wet mixture was used to cast four prototype pipe specimens. Each specimen had a wall thickness of 32 mm. Pipe specimens cast from batches 1 and 3 had a inside diameter of 203 mm and a length of 1.2 m. Pipe specimens cast from batches 2 and 4 had an inside diameter of 254 mm and a length of 1.1 m. A wire reinforcing cage was embedded in the specimen cast from batch 4.

The prototype molds were made up of a single-section inside core, an outside pipe form composed of two semicircular sections, and bottom ring plate. The surfaces within the molds were aluminum plated and had an irregular finish. A delivery cone was placed on the top of the molds to complete the formwork. Forms were hydraulically clamped on a vibrating table. The table delivered an 11,000-kg equivalent impact with an up-and-down motion. All of the prototype pipes cast failed to stand after demolding. Details including observations regarding the batching, casting, and demolding of prototypes are present in Tables 22-25 (Dauriac 1995c).

As a result of this trial, it was shown that RPC could be successfully mixed in a nonoptimized, average-sized mixture using a low w/c (0.12) and achieve an acceptable overall mixing time. It was also shown that products used as form-release agents for conventional precast mixtures were not effective for demolding RPC. Pullout tests were later performed by WES to evaluate the effectiveness of form release agents. These results are depicted in Figure 21. It was also concluded that the cage reinforcement was not adequate in preserving specimen shape after casting and immediately demolding.

It was recommended that silica flour and possibly a manufactured (angular) sand be incorporated into the mixture to improve the compactness of the RPC mixture. It was also recommended that the forms be removed by lifting instead of disassembling the molds to reduce the impact from any bond that might develop due to the use of an inadequate form-release agent.

Concrete Industries

Prototype pipes were fabricated using the dry-cast method at Concrete Industries in Lincoln, NE, in 1996. The fabrication was basically the same as that performed at International Pipe except the RPC wet mixture was replaced with the RPC dry mixture. The purpose of this trial was to determine if RPC was viable for dry-cast technology where immediate demolding of prototype pipe specimens was employed.

Table 22
Batching of Prototype Mixtures (Gifford Hill American)

Batch	w/c	Dry Mixing	Paste	Fibers Begin	Fibers End	End Mixing	Begin Casting	Observations
1	0.19	4:30	4:50 (0:20[1])	abort	abort	abort	abort	Batch was discarded because the wind blew away approximately 20% of silica fume and 15% of the cement increasing the w/c to an equivalent 0.23. The resulting mixture looked like an injection grout (very fluid, like water). Batching was terminated before fibers were incorporated in mixture.
2	0.17	4:30	6:15 (1:15[1])	6:15	9:15	11:45	17:15	A plastic liner was wrapped around the bucket of dry components. Even then, an estimated 13.6 kg of the dry components was lost to the wind. The recomputed w/c was 0.175. When fibers were added, a few balls formed but disappeared right away. Paste had good homogeneity and fiber distribution and was not sticky. This batch was used for first half of the vertical cast. When placed, sheeting effect due to fibers was observed.
3	0.17	11:30	13:00 (1:30[1])	13:00	15:00	18:15	19:00	The bags were directly dumped into the mixer. Batch had the same consistency but was a little stiffer than batch 2. A few balls formed, but were easily broken up. The temperature of concrete at the end of mixing was 15° C, a slump of 240 mm was measured, and three 102- by 203-mm cylinders were cast. This batch was used for the second half of the vertical cast.
4	0.16	10:00	13:00 (3:00[1])	13:00	15:00	21:00 (49:00[2])	48:00 (141:00[2])	The bags were directly dumped into the mixer. During mixing, it took a little longer to distribute the fibers into the paste. The mixing time was also longer. Paste was same consistency as batch 3. This batch was used for the spin casting in two placing operations. Three 102- by 203-mm cylinders were cast for each placing operation. After remixing, the second cast was made 92 min later.

[1] Time from the end of incorporation of total water and total HRWRA.
[2] Timed associated with remixing.

Table 23
Batching of Prototype Mixtures (International Pipe)

Batch	w/c	Cumulative Time (min:sec)						Observations
		Dry Mixing	Paste	Fibers		End Mixing		
				Begin	End			
1	0.15	2:00	5:20 (2:30¹)	5:20	6:20	11:20		Balls formed immediately when fibers were added. Afterwards, balls were easily dispersed with a very good distribution of fibers in the paste. The RPC looked very homogeneous and was not sticky. It had the appearance of a wet clay. The estimated slump was 150 mm.
2	0.13	1:00	5:25 (3:15¹)	5:55	7:45	11:45		Observations regarding fibers were same as those for batch 1. RPC had the appearance of a dry clay, but not sticky. The estimated slump was 0 mm.
3	0.12	1:00	8:00 (5:45¹)	8:00	9:30	14:30		Batch was very much drier than batch 2. The fiber balls were not really dispersed until the end of mixing process. It was suspected that a few fiber clumps remained in paste. The results looked very homogeneous and had the aspect of a very dry clay, but still not adhesive. The estimated slump was 0 mm. The limit of the mixer was reached in terms of mixing energy.
4	0.13	1:00	5:30 (3:00¹)	5:30	6:45	10:45		Observations for this batch were same as those for batch 2. It was a little more fluid because of water that was in mixer when mixing was begun increased w/c. The estimated slump was 25 to 50 mm.

¹ Time from the end of incorporation of total water and total HRWRA.

Table 24
Casting of Prototype Mixtures (International Pipe)

Batch	w/c	Begin Cast	Vibration[1]	End Cast	Stripping Inside	Stripping Outside	Observations
1	0.15	5	10 min @50% power	15	60	65	RPC flowed very well under vibration but collected in clumps from the top delivery cone down into the mold. On the surface of the pipe, a few bubbles more like air pockets were popping up and a thin film of water was present giving the surface a shiny look. The form was sealed with silicone around the bottom ring and along the side joint. Small bleeding along the side of the form was observed. A heavy petroleum motor oil was applied on the inside and the outside as a form-release agent.
2	0.13	10	1 min @50% power and 7 min @100% power	18	22	32	RPC flowed very well under maximum vibration but collected in sheet-shaped clumps. On the shiny top surface of the pipe, a few air pockets were emerging. The seal around the bottom ring and along the side joint was made from silicone. Small bleeding occurred along the side and at the bottom also, but still was very acceptable. The released agent (diesel) was applied on the inside core. One of the outside forms had a tool steel profiled and was coated with a liquid polymer product. The second face was heavily coated with paraffin wax.
3	0.12	10	11 min @100% power	21	25	75	RPC flow was minimum under maximum vibration and still was collected in sheet-shaped clumps. No bubbles nor a shiny surface was observed. The seal around the bottom ring and along the side joint was made from silicone. No bleeding was observed. Released agent (diesel) was applied on the inside core. The outside mold had a tool steel profiled and was coated with a liquid polymer product.
4	0.13	5	5 min @100% power	10	15	20	The observations were the same as those for batch 2. The sealing and released-agent applications were similar to those used in batch 3. A major leak at the bottom of the pipe specimen was observed. A reinforcing cage was placed inside the form prior to casting.

[1] Total time of vibration.

Table 25
Demolding of Prototype Specimens (International Pipe)

Batch	Pipe Diam. (mm)	Demolding Time (min)	Observations
1	203	65	The removal of the form from the inside core occurred without any problems. The inside surface of the pipe was regular and smooth. RPC at this stage was very adhesive compared to its adhesiveness during mixing. As the outside form was being removed, it was observed that the RPC totally adhered to the form. It stretched and fractured, by tearing, in two parts along the side joint of the outside mold without debonding from the form.
2	254	32	The form was pulled off the inside core without any difficulties. The inside wall of the pipe was smooth, except for the presence of a number of air pockets. These pockets were located in the superior half of the pipe meaning they were on their way out. The air pockets were considered fairly large for dry-cast method but not as numerous. Regarding the outside form stripping, the side sprayed with the polymer was the first to release. The face coated with the paraffin wax was very laborious to remove because of the RPC's adhesion to the mold. After demolding, the pipe slumped about 76 mm. The pipe began to bend and eventually collapsed after 5 min.
3	203	75	The first part of the demolding was like that for batch 2, except that there were fewer air pockets on the inside wall of the pipe. The removal of the outside form was easier than previously experienced but still painstaking. One side released while the other adhered to the mold. The pipe specimen had to be manipulated a lot before the second section of the outside form would release. This caused the specimen to be bent a little. After being totally demolded, the pipe slumped about 25 mm. The specimen bulged outward on the side stripped last. Fibers were exposed at the point where the pipe curved out indicating tensile failure due to the adhesion of the RPC to the form. RPC paste was not resilient any more.
4	254	20	The removal of the form from the inside core and the inside appearance of the pipe were identical to that observed for batches 2 and 3. The stripping of the outside part of the mold was similar to that for batch 3 (one side easily freed and the other required exhausting work). RPC appeared to be a little more sticky because the pipe had begun to tear along the side. When totally stripped, the outside and inside walls of the pipe looked wavy and outlined the reinforcing cage. The irregular inside wall could adversely affect flow in the pipe. After a few minutes, the pipe started to bend on one side and collapsed. Specimens cast with batches 2 and 4 were exactly the same pertaining to the diameter of the pipe, w/c of the RPC mixture, and had similar stripping times. Batch 4 had a steel reinforcing cage and batch 2 did not. Considering specimens for both batches failed to stand, it was concluded that the cage reinforcement did not provide any assistance and consequently was not adequate.

The RPC dry mixture was used to cast four prototype pipe specimens. Each specimen had a wall thickness of 32 mm. Pipe specimens cast from batches 1 and 3 had an inside diameter of 203 mm and a length of 1.2 m. Pipe specimens cast from batches 2 and 4 had an inside diameter of 254 mm and a length of 1.1 m. A wire reinforcing cage was embedded in each specimen. Forms were hydraulically clamped on a vibrating table. Cylinders were cast from batches 1 and 3 and tested by WES to determine compressive strengths (ASTM C 39 (ASTM 1995a)) and moduli of elasticity (ASTM C 469 (ASTM 1995f)) for batches. The compressive strengths were 166 and 191 MPa, respectively. The moduli were 20,600 and 21,200 MPa, respectively.

A Teflon spray was used as a form release. The mixer selected was too small. As a result, a portion of batch 1 (w/c of 0.165) had to be removed from the mixer and mixed separately. The mixture placed did not make a paste while being batched but did develop into a paste after continuous heavy vibration within the forms. The forms were removed immediately after demolding. There was some minor bonding to the outside form that required the prying open of forms and placing washers in form joints to maintain the openings for vertical lifting of the forms. All four pipe specimens stood with no signs of slumping or tilting.

As a result of this trial, it was shown that RPC is feasible for dry-cast technology where immediate demolding of prototype pipe specimens is employed. One of the problems that must be remedied for the successful production of RPC pipes using the dry-cast method is the significant time required to place and consolidate the RPC dry mixture within the forms so that the resulting RPC product is dense and free of unacceptable pockets of entrapped air.

Lafarge Canada, Inc.

Prototype pipes were dry cast using the packer-head method on December 15-16, 1997, at Lafarge Pipe and Precast in Ottawa, Canada. The purpose of this trial was to verify that RPC technology was suitable for pipe fabrication using the packer-head method of production and to fabricate a non-prestressed RPC pressure pipe with a small diameter, capable of confining an internal pressure of 1.38 to 2.07 MPa without leakage.

Two 305-mm-inside-diam, 2.3-m-long, Class 5, C-wall pipe specimens were cast. Initially, A-wall and Metric-wall pipe forms were scheduled to be used but were replaced by the thicker C-wall forms having a 70-mm thickness due to difficulties in locating the appropriate hardware. A D4 reinforcing cage having a wire diameter of 6 mm and a center-to-center spacing of 100 mm was embedded in batch-1 and batch-2 specimens. The inside concrete cover for the reinforcing cage was 30 mm.

A specimen was to be cast without the reinforcing cage using batch 3. The specimen failed because the mixture was too fluid. This was the result of the loss of dry material out the mixer discharge door due to the door being ajar. It was estimated that 13.5 percent of the powders had been lost before water was introduced. This resulted in an estimated 15-percent increase in the w/c. The

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hardware failure was not discovered until after the specimen had been cast.

Mixtures were batched using one of the production plant mixers usually dedicated to packer-head casting. The mixer was a 1.5-m^3 Eirich, high-efficiency planetary mixer consisting of a rotary pan drum with two rotary paddles having four blades each and a scrapper on the side. The loading of the mixer during production is normally performed through overhead silos. For the prototype casting, the materials were loaded through a shoot located on the side wall of the mixer. For batch 3, the fibers were loaded through a trap door located in the top of the mixer using a steel grid vibrated by an air hammer to break up fiber balls. This method of delivery greatly improved the distribution of fibers within the mixture.

The RPC dry mixture was used to cast specimens. A w/c of 0.178 was used for batches 1 and 3, and a w/c of 0.187 for batch 2. For batches 1 and 2, two thirds of the fibers were Bekeart OL 13/.16 fibers and the other third Novocon recycled tire chord fiber. For batch 3, two thirds of the fibers were Bekeart OL 13/.16 fibers and the other third Novocon Novotex fiber (Photo 4). Details including observations regarding the batching (Photo 5) and casting of prototypes are presented in Tables 26-27 (Dauriac 1997). After demolding, specimens were wetted using a water hose and covered with plastic. The specimens were then moist-cured for 24 hr followed by a 24-hr steam-cure at 90° C. Photo 6 shows the batch-1 specimen immediately after demolding. A loss of material was noted due to a second pass of the packer head through the pipe, which may have contributed to the roughness observed in the inside surface of pipes (Photo 7).

During casting, cylinders were made from batches 2 and 3. The results of compressive strength tests (ASTM C 39 (ASTM 1995a)) performed at WES are presented in Table 28. After curing, the pipe specimens from batches 2 and 3 were cut into two sections that were approximately 0.9 m in length. One of the sections cast from batch 2 was tested at the Lafarge plant using the three-edge bearing test (Photo 6) (ASTM C 497(ASTM 1995h)). The resulting ultimate load was 543 kN, which converted to a D-load of 1.85 kN/m/mm (Dauriac 1997). Pressure tests were performed at Gifford Hill using two of the remaining cut sections, one from batch 2 and the other from batch 3. The results of pressure tests showed the internal pressure capacity of the pipes exceeded the projected criterion of 1.4 to 2.1 MPa. The pressure results are presented in Table 29.

As a result of this trial casting, it was established that the mixing times have to be significantly reduced in order for RPC to be considered for conventional packer-head production. To accomplish this, it is essential that the mixing procedure be optimized to produce mixing times closer to that for conventional precast concrete. This will require the development of a system that will provide a faster and more homogeneous overhead delivery of the fibers into the mixer. It was recommended that the entire HRWRA be added to the mixture at one time instead of adding it in halves twice. Another measure that would lead to an overall reduction of mixing time is to add the fibers in the dry mixture. Wet mixing should be stopped when the material changes color and then darkens heavily. This will reduce the mixing time and provide a stiffer pipe when demolded.

Table 26
Batching of Prototype Mixtures (Lafarge)

Batch	w/c	Cumulative Time (min)			Observations
		Dry Mix	Paste[1]	Total	
1[2]	0.178	1	31	36	Dry materials were added in the following order: cement, fume, flour, and sand; and then dry mixed for 1 min. All HRWRA was incorporated in batch water and batch water added after dry mixing. The fibers were added when the mixture was still a dry powder. After 30 min of mixing, the material started to form small balls but was not shiny. Large clumps of paste and fibers appeared. Some fiber balls were present. Flow was estimated to be 0%.
2[2]	0.187	1	11	28	Dry materials were added in the following order: cement, fume, flour, and sand; and then dry mixed for 1 min. All HRWRA was incorporated in batch water and batch water added after dry mixing. The fibers were added when the mixture was still a dry powder. Mixture was extremely dry after the end of mixing, almost dusty, and did not reach shiny aspect state. Some fiber balls were present. Flow was estimated to be 0%.
3[3]	0.178	35	40	49	Dry materials were added in the following order: cement, fume, flour, and sand; and then dry mixed for 1 min. All HRWRA was incorporated in batch water and batch water added after dry mixing. All fibers were added during dry mixing time (before batch water was added). A vibrating screen was used to break up fiber balls before fibers entered mixture. This resulted in a very good distribution of the fibers. Mixture had the appearance of top soil and then turned into a very fluid paste not suitable for packer-head casting. Flow was estimated to be 30%.

[1] Paste was dark in color and had a shiny aspect.
[2] Volume of fibers in mixture was 2.2% in which 2/3 volume was OL 13/.16 and 1/3 volume was Novocon recycled-tire cord.
[3] Volume of fibers in mixture was 2.2% in which 2/3 volume was OL 13/.16 and 1/3 volume was Novotex.

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Table 27
Casting of Prototype Mixtures (Lafarge)

Batch	Time (min:sec)		Stripping		Observations
	Casting	Vibrating	Inside	Outside	
1	5:00	10:00	0:30	0:30	Two passes of the packer-head were made through the pipe. The second pass resulted in loss of material from the wall of the pipe. There were some dry spots on the outside surface. The RPC exhibited a small amount of resilience. The inside surface appeared slightly rough with the ends of some fibers exposed but was considered acceptable by HDR. The outside surface was sprayed with water and covered with a plastic sheet to avoid drying.
2	2:00	2:00	0:30	0:30	Two passes of the packer-head were made through the pipe. The second pass resulted in loss of material from the wall of the pipe. Numerous air pockets and fiber balls were observed on the outside surface of the pipe. Some of the fiber balls had no paste and appeared brass colored. Two traverse cracks with an estimated 2-mm-maximum width were located approximately 410 and 610 mm from the bottom (bell end) of the pipe. The crack farther from the bottom extended approximately a third of the way around the pipe, and the other was less than a third the first crack length. The inside surface appeared wavy but was considered acceptable by HDR. The outside surface was sprayed with water to avoid drying.
3	0:00	0:00	0:00	0:00	Mixture was too fluid; casting aborted.

Table 28
Compressive Strengths for Prototype Mixtures (Lafarge)

Batch	Specimen	Compressive Strength, MPa
1	B1	146
	B2	246
	B3	173
	Average	188
2	C1	174
	C2	118
	C3	196
	Average	162

Table 29
Pressure-Test Results for Lafarge Prototype Specimens

Batch 1		Batch 2	
Pressure MPa	Observation	Pressure MPa	Observation
0.69	No Seepage	0.69	No Seepage
1.38	No Seepage	1.38	No Seepage
2.07	No Seepage	2.07	No Seepage
2.76	No Seepage	2.76	Seepage from Fiber-Ball Void
2.83	Seepage from Full Length Longitudinal Crack	1.38	Seepage Continued
0.00	Start Retest	2.76	Seepage from Multiple Longitudinal Cracks
0.69	No Seepage	0.00	Start Retest
1.38	No Seepage	1.38	Seepage at Bottom Seam and at Top from 254-mm-Long Crack
2.07	Seepage from Full Length Longitudinal Crack	2.76	Seepage from Multiple Longitudinal Cracks, Maximum Pressure
2.76	Seepage Continued	--	--
3.10	Seepage Continued	--	--
3.45	Seepage Continued	--	--
3.79	Seepage Continued, Maximum Pressure	--	--

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5 Discussion

One of the first tasks of the CPAR project was to simulate the hardened properties of the RPC 200 reported by Bouygues through analyses performed by WES on products made using similar ingredients. Materials for mixtures were selected through evaluation of trial mixtures to determine their potential for producing optimum rheology and strengths in prototype mixtures. Two mixtures, one flowable, designated as the wet mixture, and the other zero-slump, designated as the dry mixture, were selected as representative of RPC pipe-production mixtures.

The fibers for both mixtures proved painful to those who prepared or handled the specimens as the injection-needle-like fibers would penetrate any glove. When batched, the RPC dry mixture consisted of sizeable balls of paste with protruding fibers (Photo 3). In casting of the test specimens, the dry mixture had to be heavily rodded in order to compact material into molds. It was found that the dry mixture did not flow when vibrated on a table normally used to consolidate conventional mixtures. When specimens were demolded, open seams were evident at the interface between some of the compacted balls. It was expected that these seams would result in lower strengths for the dry mixture; however, only flexural- and fatigue-strength results reflected lower strengths. The preparation of the wet-mixture specimens was similar to that for conventional concrete with no signs of defects.

The averages for compressive strength, flexural strength, and modulus of elasticity fell within the range of values reported by Bouygues (Richard and Cheyrezy 1995). The average tensile strengths for the wet and dry RPC mixtures were considered conservative. Many specimens failed at the interface because the tensile strength of the RPC was near that of the epoxy adhesive used to bond the specimen to the end caps. These strengths were comparable with the direct tensile strength stated for RPC 200 in *VSL News* (1997). The shear and fatigue strength data for both wet and dry mixtures had significant variance. The direct-shear values for the angle of internal friction and cohesion are invalid due to the poor correlation of test results. It was believed that more consistent results could have been attained by testing larger specimens. However, this was not possible as the test apparatus was already being operated at maximum capacity due to the high strength of the RPC.

Other tests performed by WES indicate that RPC will perform well in cavitation-erosion and sulfate environments in comparison with other concretes. Results of a study to determine the effects of seawater on the

corrosion of mild steel that was placed in RPC at different depths indicate that specimens are performing well after more than 2 years of exposure.

More energy was needed to mix RPC than conventional concrete. This was experienced both in the laboratory and field when attempts were made to batch RPC using the maximum mixer load for conventional concrete. In these cases, the mixer stopped due to overload, and the RPC load had to be discarded or partly removed and mixed in two loads.

The nature of RPC at the extremely low water-to-binder ratios makes the material very cohesive and, under some circumstances, difficult to remove from the formwork when it is only minutes old. It was also shown that form-release agents used for conventional precast mixtures were not effective for demolding RPC. It is, therefore, important that the performance of any form-release agent be proven effective before being used for casting RPC products.

RPC prototype specimens were successfully cast using the wet-cast, spun-cast, dry-cast, and packer-head methods. The compressive strengths for RPC prototype specimens were in the range of 140 to 200 MPa. These specimens were steam-cured for 24 hr at 70° to 90° C. The C-wall pipe specimens cast at Lafarge using the packer-head method performed well in both the pressure and three-edge bearing tests. Specimens showed no signs of leakage for internal pressures of 2.07 MPa and less. The ultimate D-load was approximately 10 times that for conventional precast pipes fabricated at the Lafarge plant.

At Gifford Hill, significant cracking occurred in the hardened prototype pipe specimens due to drying shrinkage. This succeeded in a reduction of the load capacity for the prototype pipes. To minimize cracking in RPC precast pipes, HDR has provided the following guidance:

   a. Protect specimens from moisture loss immediately after casting as drying of the RPC product at any time prior to the completion of the steam-curing period can cause cracking.

   b. Remove any mechanism that is a restraint against shrinkage as it will cause tensile stresses in the RPC.

   c. Do not preheat specimens above 55° C prior to steam-curing as this can cause cracking that will result in lower strengths.

During fabrication of spun-cast cylinders prior to casting prototype specimens at Gifford Hill, it was observed that fibers were concentrated in the outer third of the cylinder walls. This potential for segregation during spin-casting was deemed unacceptable by the industrial partners.

At Gifford Hill, it was also determined that pumping RPC caused a general orientation of the fibers in the direction of the axis of the pipe and a longitudinal seam to form where flows around the inside pipe form met. The orientation of the fibers combined with the longitudinal seams reduced the hoop-stress capacity of the pipe.

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The estimated times required to batch conventional precast concrete mixtures are approximately 45 sec for dry mixing and 1 min for wet mixing according to the plant manager at the Lafarge plant. To achieve batching times nearer the Lafarge times, HDR suggested that all powders and fibers be added before dry mixing, that all the HRWRA be included in the mixture water before wet mixing, and that the mixing be terminated when the paste starts to form as indicated by heavy darkening of mixture's color. A better fiber delivery system is needed to reduce loading time and balling of fibers. The use of a steel grid vibrated by an air hammer reduced the occurrences of fiber balls and improved the distribution of fibers in the last mixture batched at Lafarge.

The production of C-wall RPC pipes is not economically viable for small-diameter pipes (Dauriac 1997). A thinner wall pipe will have to be designed and proven economical in order to be competitive. The pipe should have a minimum concrete cover of 9.5 mm over the cage reinforcement and minimum thickness to accommodate a pressure joint. The target range for the wall thickness should be 25 to 31 mm.

HDR concluded that a more state-of-the-art packer-head was better suited for RPC production. In response, Lafarge is presently working to upgrade their packer-head equipment by adding a vibrating screed on the lower end of the head. Once retrofitting has been completed, HDR will attempt to reschedule manufacturing of prototype pipes at Lafarge.

6   Conclusions

The results from WES hardened property tests are in agreement with properties reported by Bouygues. It should be expected that these hardened properties for RPC 200 will be different from those reported for prototype mixtures because of differences in curing. Other WES results indicate that RPC will perform well in cavitation-erosion, sulfate, and seawater environments in comparison with other concretes.

The objective of the research was revised in June 1997 to eliminate any additional efforts to produce precast pile products based on an economical analysis of their competitiveness with existing pile systems. HDR concluded that RPC piling would have improved performance in an aggressive environment. However, the projected price for the RPC pile products would greatly exceed other available options.

HDR also concluded that RPC culvert and sewer pipes are technically feasible from a production standpoint. However, only sanitary sewer products appear to be economically viable as the culvert and conventional storm-sewer applications appear to be well served by products currently on the market. Based on the successful performances of packer-head specimens in pressure and three-edge bearing tests, research should be continued in the development and commercialization of packer-head production techniques for sanitary sewer pipe.

Form-release agents used for conventional precast mixtures were not effective for RPC mixtures. The performance of any form-release agent should be proven effective before being used for casting RPC products.

Pumping is not a viable method for production of pipes from RPC due to a general orientation of fibers in one direction.

Improvements in loading and mixing of materials during batching are needed in order to achieve batching times nearer those for conventional precast concrete and to eliminate the occurrences of fiber balls and provide a better distribution of fibers within the mixture. Multiple passes of the packer-head through the pipe during casting resulted in the loss of material and an irregular inner surface, and therefore, should be prohibited.

The production of C-wall RPC pipes is not economically viable for small-diameter pipes. A thinner wall pipe will have to be designed and proven economical in order to be competitive.

At present, no CPAR/RPC product has proven ready for industrial production.

7   Recommendations

Based on the successful performances of packer-head specimens in pressure and three-edge bearing tests, it is recommended that HDR continue its research in the development and commercialization of packer-head production techniques for sanitary sewer pipe. It is also recommended that the suggested improvements resulting from the trial casting at Lafarge for changes in loading and mixing of materials during batching be refined and implemented to achieve batching times nearer those for conventional precast concrete and to eliminate the occurrences of fiber balls and provide a better distribution of fibers within the mixture. Research to incorporate the less expensive Novocon recycled-tire cord fibers and an optimum wall thickness should be continued in the pursuit of an economically viable RPC sanitary sewer pipe.

8 Commercialization

The first phase for the commercialization of RPC was to make the precast industry aware of the technology developed by Bouygues and HDR and to promote its potential application in creating a new line of superior precast products. This was accomplished through papers, one of which was presented at the Third National Concrete and Masonry Engineering Conference in San Francisco (Dowd and O'Neil 1995) and another that was selected as a finalist in the Civil Engineering Research Foundation's first Innovations Award in Washington, DC (Dowd 1996); articles in engineering magazines; and oral presentations at engineering committee meetings and associations. The success of this first phase of commercialization facilitated the recruitment of material and precast industry participants needed to accomplish the prototype fabrications reported.

The second and final phase for the commercialization was to be the transfer of the developed RPC precast technology. However, this cannot be accomplished within the CPAR Program as the technology is still being developed for the production of RPC precast pipes. At present, Lafarge is working to upgrade its packer-head equipment. Once retrofitting has been completed, HDR will attempt to reschedule manufacturing of prototype pipes at Lafarge. If the production of RPC prototype pipe is successful, HDR will undertake the task of scheduling demonstration projects to market the product to pipe manufacturers and will work to change construction specifications to allow RPC pipe as an alternative to conventional precast sewer pipe.

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    d. Designation C 157. "Standard test method for length change of hardened hydraulic-cement mortar and concrete."

    e. Designation C 230. "Standard test method for flow table for use in test of hydraulic cement."

    f. Designation C 469. "Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression."

    g. Designation C 497. "Standard methods of testing concrete pipe, manhole sections, or tile."

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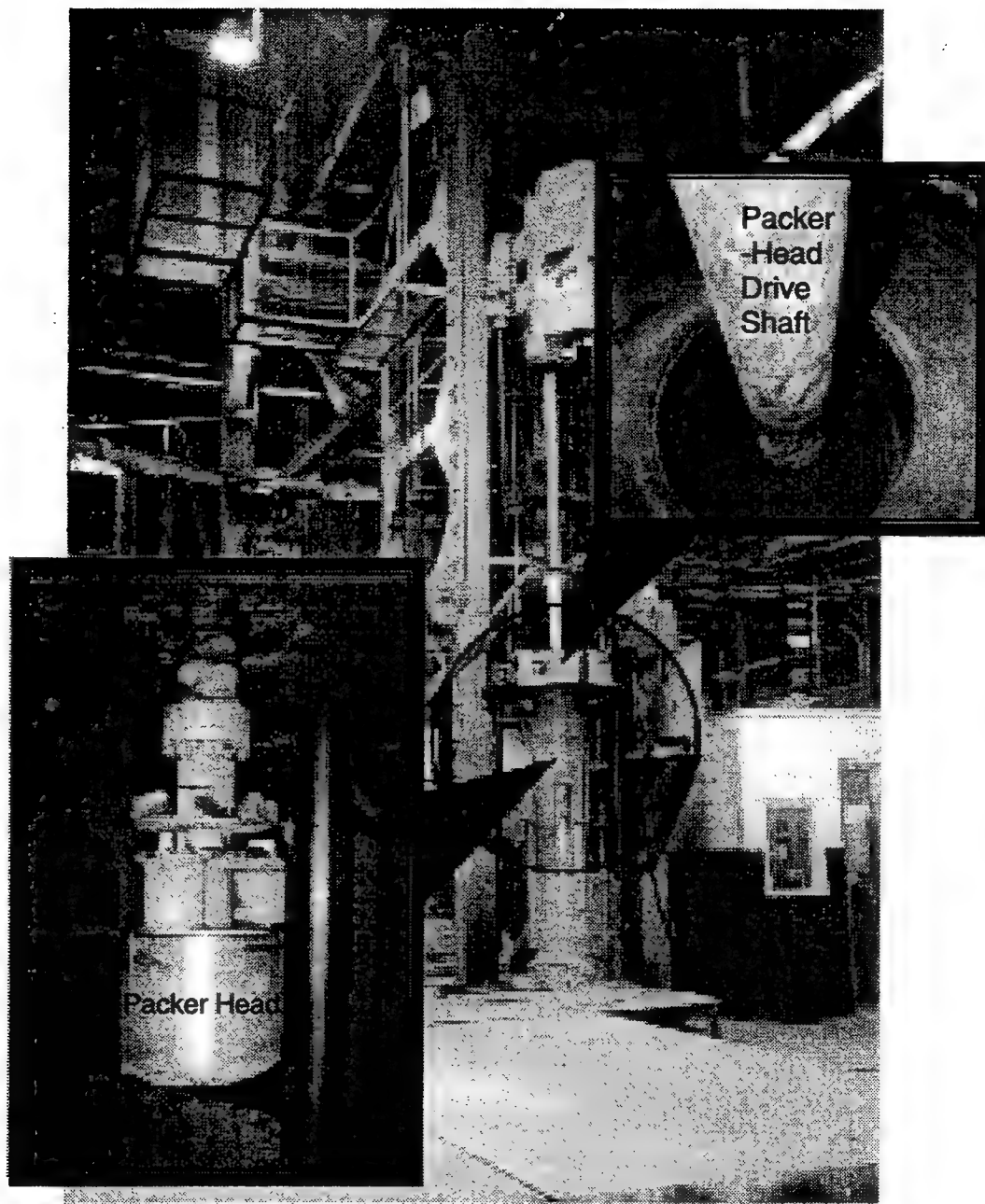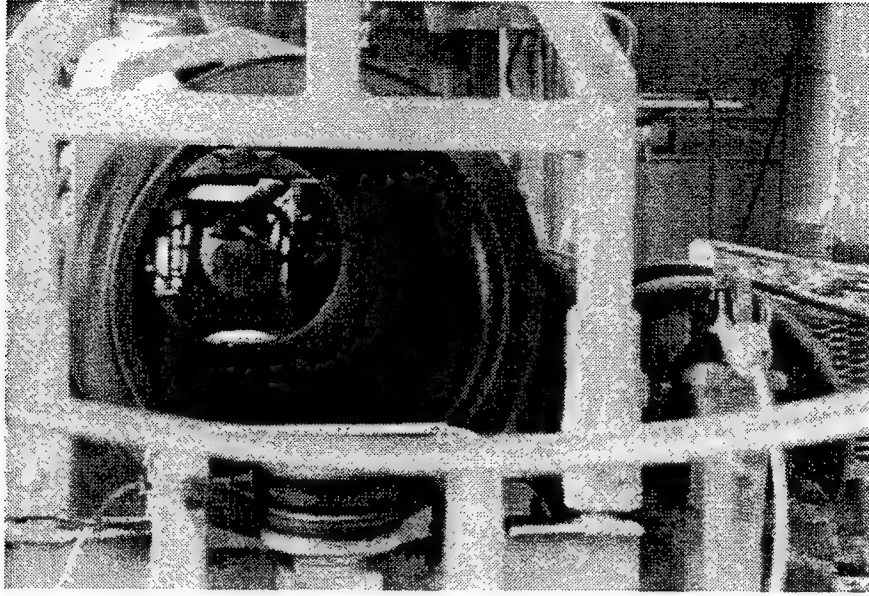
Photo 1. Packer-head equipment

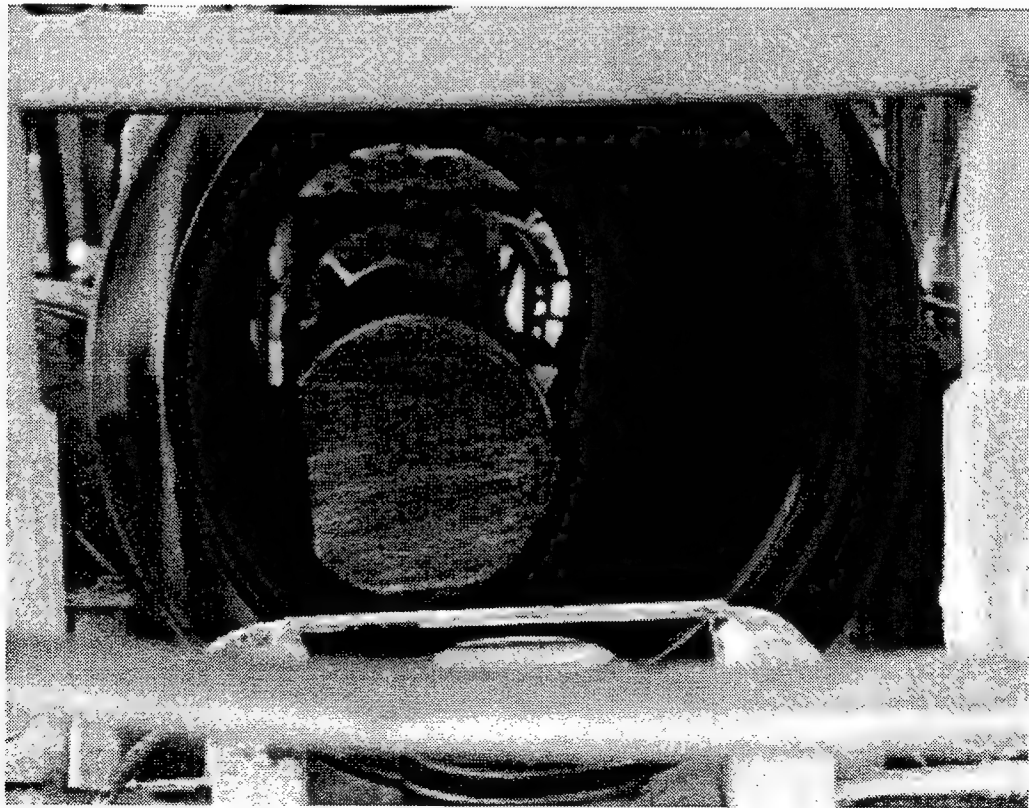Figure 2. Loading RPC batch into tongue during spin casting

Photo 3. Emptying RPC batch from tongue into spinning form
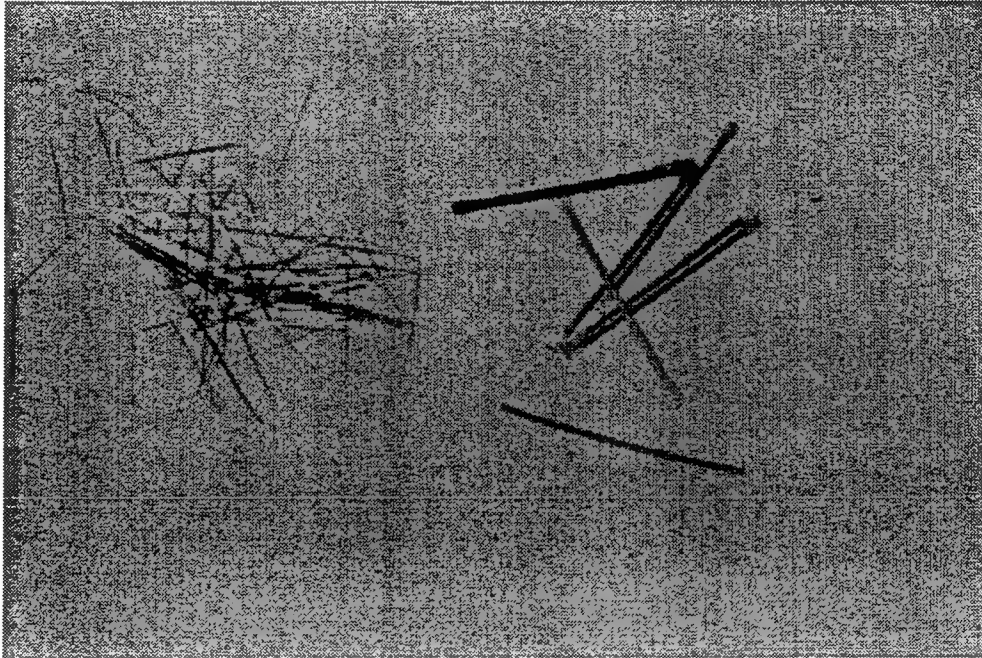
Photo 4. OL 13/.16 (smaller) and Novotex fibers

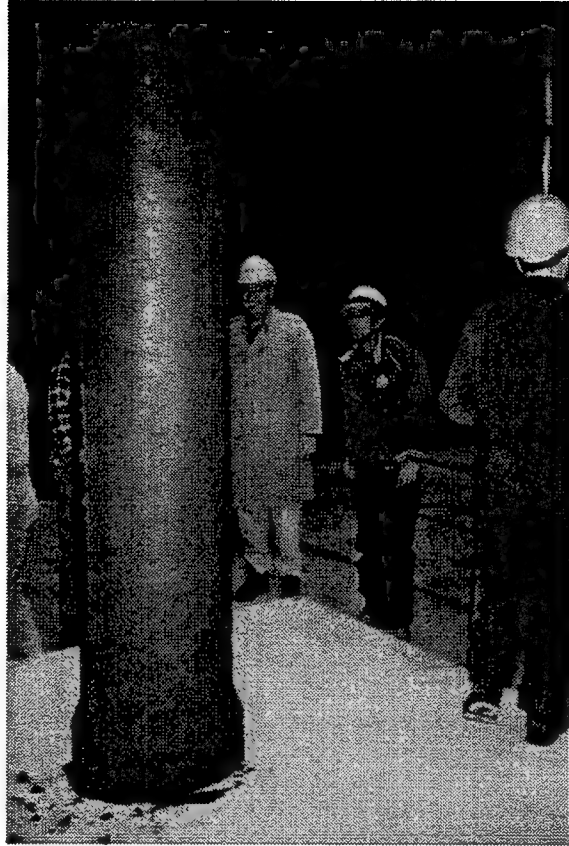Photo 5. Mixture has reached paste stage and is ready to cast
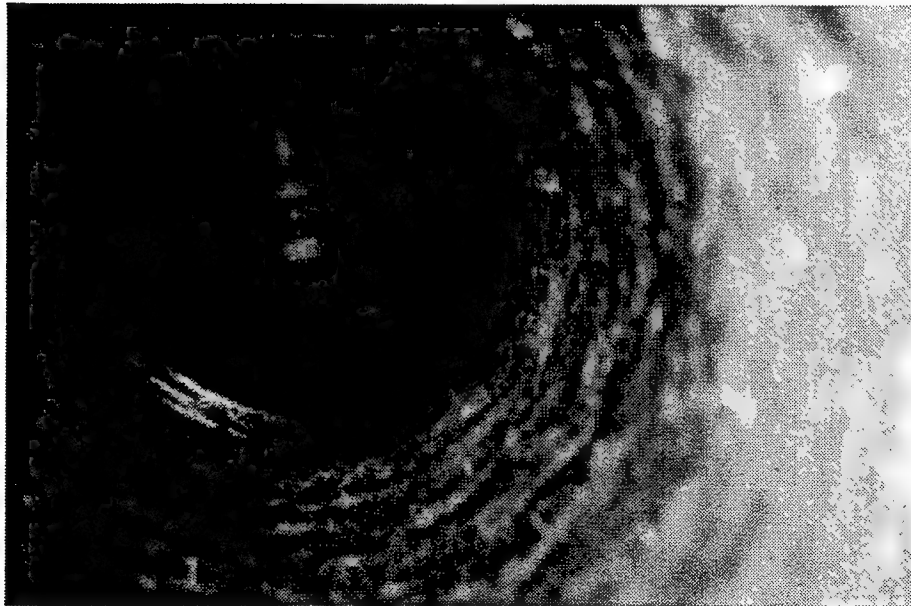
Photo 6. Prototype pipe immediately after
demolding

Photo 7. Inside surface of pipe

Photo 8. Three-edge bearing test

Appendix A
Petrographic Examination of Eleven Silica-Fume Products for Reactive Powder Concrete

Corps of Engineers   Petrographic Report   Structures Laboratory
Waterways Experiment   3909 Halls Ferry Road
Station   Vicksburg, MS 39180-6199

SUBJECT: Petrographic Examination of Eleven SF for CPAR/HDR Project

31 Aug 95

1.   Mr. Ed O'Neil, CEWES-SC-CE, requested a petrographic examination of 11 silica fumes (SF) that
he furnished in Jul 95. The purpose for the examination was to establish whether or not particle- size
range of the SF, or another recognizable chemical or physical feature, might be contributing to observed
differences in the flow characteristics of each fume. Also, he requested that the data on particle
composition, size, and shape gathered from fume 950188 be compared to the data from the other samples
to determine which one of the SF samples is more nearly like sample 950188. The Concrete Technology
Division (CTD) numbering system was used to identify the fumes. The number assigned each fume is
given below,

CTD Identification	Source
950056	Elkem, Undensified
950214	Elkem, ES 900W
950307	Elkem, EMS 965
950342	8030 Globe Silica Fume, "Regular"
950343	8030 Globe Silica Fume, "Low Density"
950344	8030 Globe Silica Fume, "Compacted"
950361	Elkem, ES 900W
950182	Elkem, ES 900W, Undensified
950349	Elkem, 940-U-P. France
950188	Elkem, EMS 960
950499[1]	MST Fume, France (Zirconium Fume)

2.   The 11 SF samples were examined visually, and a color was assigned to each fume using the Rock-
Color Chart[2] prepared by the Geological Society of America. Examination of each fume using the high-
magnification and high-resolution capabilities of a scanning electron microscope (SEM) was done. The
energy dispersive X-ray (EDX) unit attached to the SEM was used to determine the chemistry of the
fumes. Semiquantitative chemical data were also obtained from each fume. An X-ray diffractometer
(XRD) was used to examine two of the SF samples suspected to contain crystalline phases. Sampling
techniques and procedures for examination using the SEM, EDX, and the XRD are given below:

        SEM. The SEM samples were prepared by placing about 0.1 g of SF in a small beaker with
        100 mL of methanol. The beaker was placed in the tank of an ultrasonic cleaner partially filled
        with water and vibrated for approximately 10 min. The intent was to disperse the particles as
        much as possible prior to examination with the Hitachi S-2500 SEM. A clean pipette was used to
        place a drop of the methanol with suspended particles of SF on an SEM sample stub. This
        procedure was repeated for each sample. The samples were coated with a thin layer of gold
        (approximately 15 nanometers (nm) thick) to make them conductive.

        EDX. The samples used for EDX examination were prepared by forming a tightly packed powder
        of each SF sample. The powderpack was made using a standard sample holder furnished with the

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[1]   This sample was received from France after investigation was initiated.
[2]   The Rock Color Chart Committee, E. N. Goddard, Chm, "Rock Color Chart," 1992, The Geological Society of America,
Boulder, CO.

Appendix A   Petrograhic Examination of Eleven Silica-Fume Products for Reactive Powder Concrete

powder X-ray diffractometer (Philips model No. 1800). This method provides a homogeneous sample. It is not necessary to coat it with a metal to make it conductive.

XRD. The XRD samples were examined as tightly packed powders of a composite of each of samples 950188, 950344, 950182, and 950499. Approximately 5 g of sample 950182 was wet sieved through a 45-µm (No. 325) sieve. The material larger than 45-µm-diam was dried, ground, and examined as a tightly packed powder. This was done to assist in the identification of some crystalline material found in some samples.

Results

3.   The visual examination of the samples showed that some contained small compacted beads of tiny SF particles and others contained irregularly shaped nodules of fume that were very loosely held together. Sample No. 950344 appeared to have more of the compacted beads than the rest. Other fumes containing beads were 950342, 950349, and 950182. Fume samples 950056, 950214, 950307, 950342, and 950361 all contained irregularly shaped nodules that were probably accidentally formed as the SF was produced. Fume 950188 did not appear to have nodules or compacted beads. Data obtained from the Rock Color Chart concerning the color of the fumes are given in Table A1.

4.   Figures A1 and A2 are SEM photomicrographs of the white-colored fume from France (950499), and fume 950214, respectively. Number 950214 was also a light-colored fume. The micrographs show typical morphology and physical characteristics of the light-colored fumes, which also include fumes 950182 and 950361. The SEM analysis showed that the fumes were all a fine powder, composed of individual spherical particles and of particles of spheres and other shapes welded or fused together. The fused particles usually consisted of lathlike and equant grains, as well as spherical particles. Some particles were massive with unrecognizable forms fused together. Spherical and irregularly shaped particles were present with numerous smaller particles fused to their surfaces. These fused particles of lathlike and equant grains and unrecognizable forms were more abundant in the light-colored fumes,

5.   Figures A3 and A4 are SEM photomicrographs of two of the darker colored fumes. Figure A3 shows fume 950344, and Figure A4 shows fume 950343. These figures show typical morphology and physical characteristics of dark-colored fumes 950056, 950307, 950342, 950349, and 950188. The SEM photomicrographs indicate that more of these fumes are individual spherical particles than what is present in the light-colored fumes. Also, note that the surfaces of these particles are usually smooth with very few having smaller particles fused to their surface. While tiny agglomerates of fused particles are present, a study of the SEM photomicrographs indicated that fewer were present in the dark-colored fumes than were present in the light-colored fumes. The agglomerates in both photomicrographs appear to be agglomerates of individual particles rather than particles that are fused together.

6.   Figures A5 and A6 are SEM photomicrographs of SF 950056 and 950188, respectively. The photomicrographs were made at lower magnification to give a better overall view of the two. After an in-depth study of the SEM and EDX work, it was decided that fume 950056 had physical and chemical characteristics more like those of fume 950188 than any of the rest. The chemistry of each was similar, and their morphology is similar. The agglomerates of fume in both photomicrographs are less than 7-µm-diam; many are as small as 1 or 2 µm on their long axis. Both fumes appear to have more particles with smaller diameters than the rest, giving a smaller average diameter.

7.   Table A2 lists the chemical and semiquantitative chemical data obtained from the EDX analysis. The silicon (Si) contents are similar with a low of 93.52 percent, up to 96.32 percent. The fume from France had the fewest components, with only three elements detected by EDX. These three were Si, aluminum (Al), and zirconium (Zr), The Al and Zr was much higher in this sample than they were in the others. The table shows tin (Sn) in all the fumes except fume 950349. Tin was tentatively identified since

the sum peak of Si is also close to the excitation energy of the L alpha line of tin. The instrument in its current configuration could not resolve the two peaks.

8.   XRD data from two samples are shown in Figure A7. The darker line on the pattern is sample 950361, one of the light-colored fumes. The lighter colored line is fume 950344, one of the dark-colored fumes. It was assumed that sample 950361 is typical of all the light-colored fumes and sample 950344 is typical of all of the dark-colored fumes. Other samples of light-colored silica fume which were examined by XRD indicated that the two light-colored samples contained more crystalline material than the dark-colored samples. The crystalline phases in 950361 and the material larger than 45-μm-diam from this sample were identified by XRD as ZrO_2 (zirconium oxide), a calcium zirconium oxide, and zircon. The major crystalline phase in the sample is probably calcium zirconium oxide. XRD analysis of the crystalline phases present in sample 950344 indicates no Zr phases compared to 950361. Instead there is a trace of quartz (SiO_2) and Moissanite (SiC). The amorphous hump shown in Figure A7 (at approximately 22 deg two-theta) is slightly higher in intensity for sample 950344 (red trace) than it is for sample 950361 (black trace). This indicates that there is slightly more glass (amorphous material) and less crystalline material than in sample 950344 compared with 950361. This is consistent with the rest of the XRD record that shows more crystalline phases (more diffraction peaks) in sample 950361. The XRD results obtained from other light-colored samples were consistent with those from the composite sample 950361. Zirconium oxide peaks were present in patterns obtained from these samples.

Discussion

9.   The SEM approach to comparing particle-size ranges of the fumes was generally successful. The average size of particles in each fume can be determined by tabulating measurements of particles in the photomicrographs if this is needed. Single spherical particles as small as 0.05-μm in diameter and as large as 2 to 3 μm in diameter were present in samples examined. Wet sieving of fume 950182 proved that at least some of that sample consisted of particles larger than 44 μm in diameter. Although a dark fume was not wet sieved, the photomicrographs indicated that the dark-colored SF samples did not have as much large material as the light-colored fumes had. As already mentioned, fumes 950188 and 950056 (Figures A5 and A6) appeared to be more similar, and one of the characteristics that this was based on was the fact that the photomicrographs showed both had more particles that were smaller in diameter than the other SF samples.

10.   The dark-colored and light-colored fumes also differed in the shapes and the surface textures of the particles present. In the light-colored fumes, nodules were fused to the surface of larger particles. This was a consistent characteristic of all the light-colored fumes and was hardly present in the dark-colored fumes. The light-colored fumes had more particles that were not spherical than the rest, and often the particles were fused together, making single particles with the long axis up to 2 or more Am. In general, the dark-colored fumes had smoother surfaces and more unfused (spherical) particles. This would suggest that the dark-colored fumes having more spherical particles have fewer interlocking grains and would have a higher flow. However, discussion with Mr. Ed O'Neil has revealed that the opposite is the case, that the light-colored fumes, with the odd shapes and fused particles are actually the ones that impart the highest flow when used in concrete mixtures.

11.   The EDX chemical data did not show anything that could be used to explain the low or high flows obtained by any particular fume. Additional XRD data combined with the chemical data might shed more light on this question.

12.   The XRD data have shown that the light-colored fume examined has more crystalline phases and less glass than the dark-colored samples examined. These crystalline phases would not be pozzolanic and would probably cause slower hydration in the early stages and slower strength gain. As already mentioned, the assumption was made that the composition of the other fumes was consistent with the two that were examined. The light-colored fume from France had a composition similar to the light-colored

A4

fume that was examined (950182). More of the fumes may need to be examined by XRD to determine if the light-colored ones are consistently more crystalline than the dark-colored fumes.

13. At the beginning of this study a tentative hypothesis had developed that the more spherical grains would show the greatest fluidity when mixed into the concrete paste. The results obtained do not support this idea. The results instead suggest that the more reactive the SF is, the more it will hydrate quickly and the resulting gel will increase the stiffness of the mixture. The rounded glassy SF samples definitely are less crystalline and do stiffen the mixture.

Conclusion

14. Additional work will be needed to produce a decisive answer to the variation in flow characteristics of each of the fumes. The varying amount of crystalline material in the fumes may be the answer. Additional work, especially XRD work, would help in demonstrating that all fume samples with good flow characteristics are more crystalline. Thermal studies would also be helpful if they can be used to show that the less-reactive (more crystalline) silica-fume samples have the better flow characteristics.

15. If the reactivity of the SF is important to the flow characteristics of the resulting cement mixture, it may be possible to intelligently select the best of the SF fumes by measuring the heat evolution in a classical pozzolan-hydration test. It may also be possible to select SF materials that hydrate but react more slowly than conventional SF and consequently retain the fluidity that is needed for placement, but still produce an ultimate strength that is as high as would be obtained with a highly reactive SF; it should be worthwhile to conduct some thermal studies.

Table A1
Color Data[1] for 11 Silica Fumes

Sample ID	Color	Hue, Value, and Chroma
950056	medium bluish gray	(5B 5/1)
950214	very light gray	(N8)
950307	medium bluish gray	(5B 5/1)
950342	light gray	(N7)
950343	light bluish gray	(5B 7/1)
950344	medium bluish gray	(5B 5/1)
950361	light gray	(N7)
950182	very light gray	(N8)
950349	medium bluish gray	(5B 5/1)
950188	medium bluish gray	(5B 5/1)
950499	white	(N9)

[1] From "Rock Color Chart," 1992, the Geological Society of America, Boulder, CO.

Table A2
Chemical and Semiquantitative Chemical Data for 11 Silica Fumes

ID	Sample Elements Present, percent[1]										
	Si	Al	Mg	Zr	K	Fe	Ca	Sn	Na	S	Cl
950056	96.15	1.16	[2]	[2]	0.76	[2]	[2]	0.79	0.80	0.22	0.12
950214	95.16	2.07	[2]	0.32	0.14	0.22	0.20	0.88	0.81	0.20	[2]
950307	95.93	1.04	[2]	0.21	0.54	0.01	[2]	1.12	0.73	0.27	0.15
950342	96.29	0.79	[2]	0.24	0.63	[2]	[2]	0.82	0.86	0.27	0.10
950343	96.32	0.90	0.07	0.12	0.55	[2]	[2]	0.78	0.96	0.22	0.08
950344	93.52	0.84	3.04	0.36	0.60	0.17	0.07	0.73	0.62	[2]	0.04
950361	94.93	1.98	[2]	0.19	0.18	0.08	0.86	0.81	0.73	0.24	[2]
950182	95.72	1.92	[2]	0.09	0.13	0.11	0.69	0.46	0.88	[2]	[2]
950349	93.68	0.29	1.28	0.50	2.01	0.14	[2]	[2]	1.72	[2]	0.39
950188	95.61	1.74	[2]	0.12	0.42	[2]	0.07	0.59	1.39	[2]	0.05
950499	94.03	4.76	[2]	1.21	[2]	[2]	[2]	poss	[2]	[2]	[2]

[1] Assumed 100 percent for each sample.
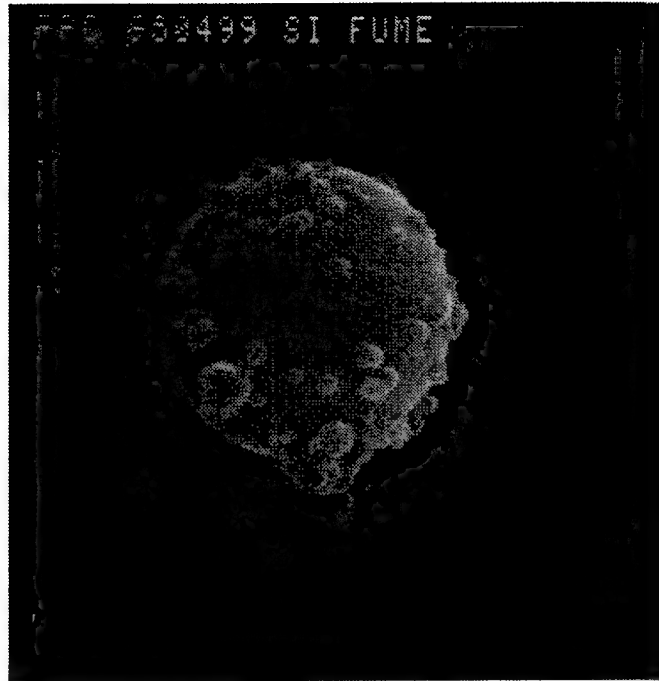[2] Not detected.
poss Possibly present as trace amount.

Figure A1. 950499 fume from France. The particles often had smaller nodules fused to their surface. Small agglomerates of several particles fused together were in this sample (25,000X)
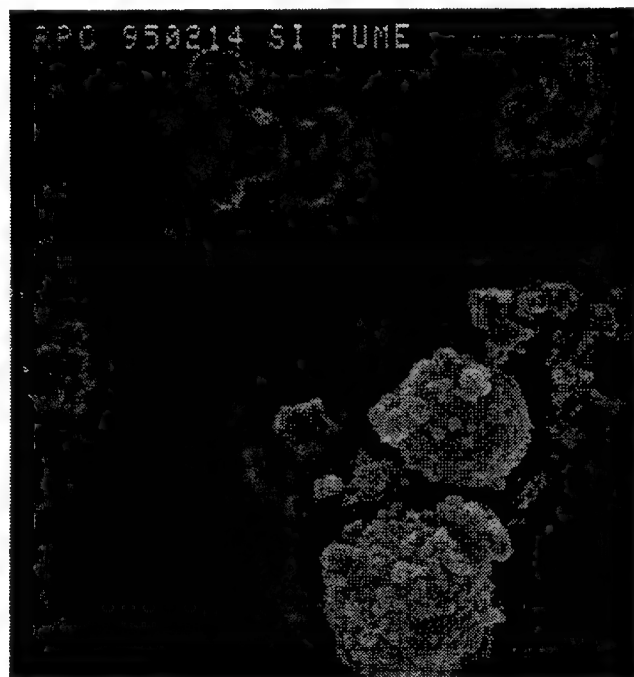

Figure A2. 950214 fume. This was one of the light-colored fumes. Small nodules are fused to the surface. Spheres and lathlike and equant grains were often fused together. Small agglomerates are present (15,000X)
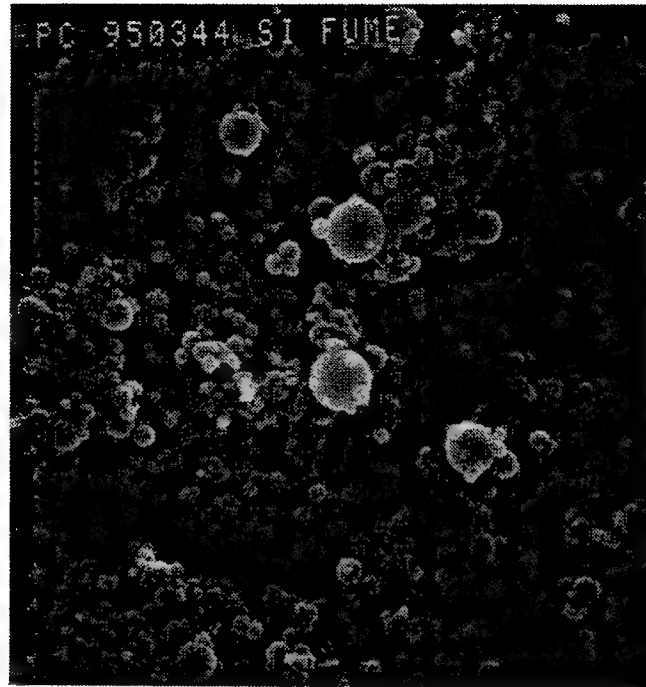
Figure A3. 950344 fume. This is one of the dark-colored fumes. The surface of the spheres are nearly free of the nodules. Individual spherical particles seem to be more abundant. Some agglomerates are present (15,000X)
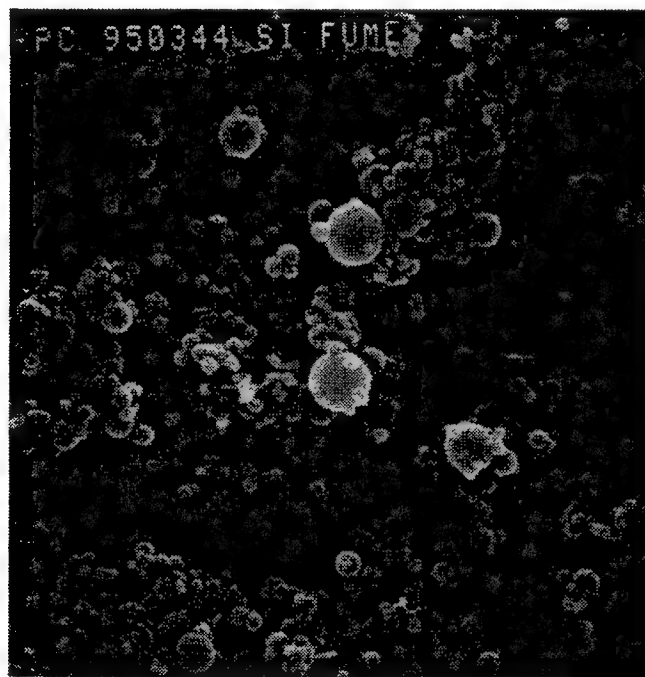
Figure A4. 950343 fume. This is another dark-colored fume. It is very similar to the fume in Figure A3. Some agglomerates are present (15,000X)
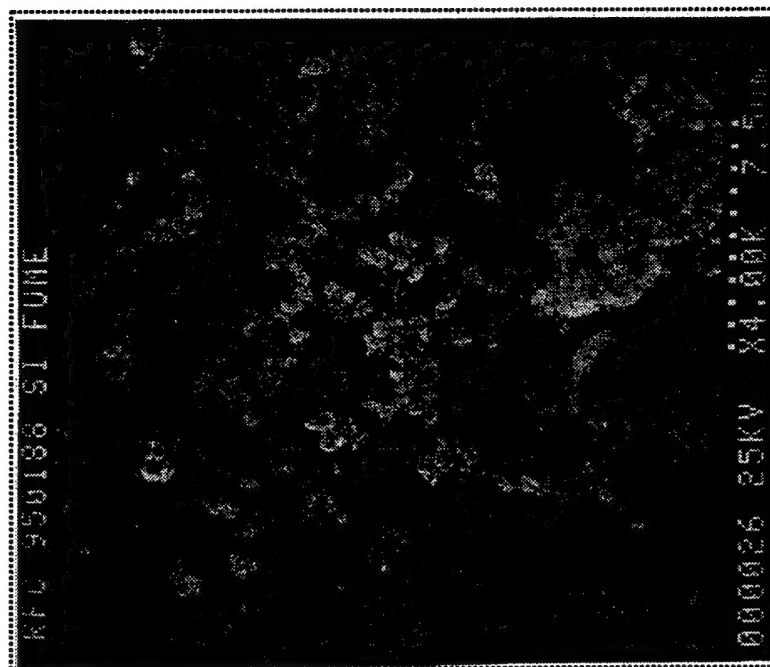
Figure A6. 950056 fume

Figure A5. 950188 fume

(Fume 950056 was selected as being the best match to fume 950188 based on chemical and physical characteristics. Both appear to have spherical particles with a smaller average size than usual. Some agglomerates are shown in both photomicrographs)
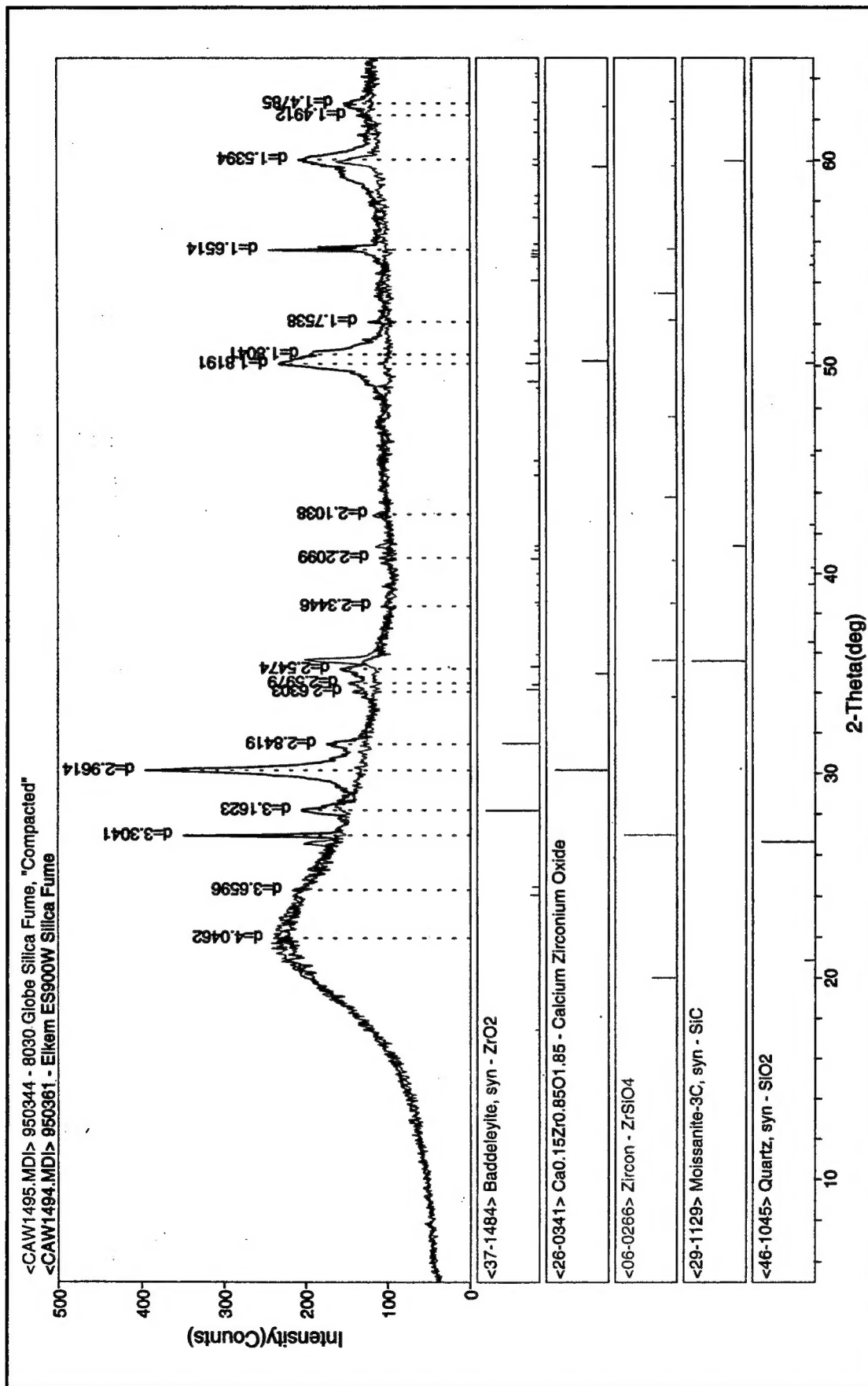
Figure A7. XRD patterns of Elkem ES ES 900W [9503611] and 8030 Globe "compacted" [9503441] silica fumes. Note that both samples are dominated by the amount of amorphous material. The Elkem ES 900W was darker colored and contained Zr-rich crystalline phases. The 8030 Globe "compacted" silica fume was lighter colored and contained Si-rich crystalline phases

Appendix A   Petrograhic Examination of Eleven Silica-Fume Products for Reactive Powder Concrete

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Reactive Powder Concrete for Producing Sewer, Culvert, and Pressure Pipes

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13. ABSTRACT *(Maximum 200 words)*

This report documents research to develop and demonstrate the technical and economic viability of reactive powder concrete (RPC) a very-high-strength, high-performance concrete material) for producing precast sewer/culvert and pressure pipes with the ultimate program goals of gaining construction industry acceptance and implementing wide-scale commercial fabrication of these products. By optimizing the design of the precast RPC pipes, it was projected that commercially competitive, lightweight units could be produced that would reduce handling, shipping, and installation times and provide improved resistance to attack by sulfates and other chemicals.

Two mixtures, one flowable and the other zero-slump, were selected as representative of RPC pipe production mixtures, and the hardened concrete properties were determined for each mixture.

RPC prototype specimens were successfully cast using the wet-cast, spun-cast, dry-cast, and packer-head methods. The compressive strengths for RPC prototype specimens were in the range of 140 to 100 MPa. These specimens were steam cured for 24 hr at 70° to 90° C. The C-wall pipe specimens cast at Lafarge using the packer-head method performed well in both the pressure and three edge bearing tests. The Lafarge specimens showed no signs of leakage for internal pressures of 2.07 MPa and less. The ultimate D-load was approximately 10 times that for conventional precast pipes fabricated at the Lafarge plant.

(Continued)

14. SUBJECT TERMS

High-performance concrete material	Reactive Power Concrete
Packer-head production	Sewer pipes
Precast pipes	Very-high-strength
RPC	

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13. (Concluded).

Based on results from casting of prototypes, it was concluded that RPC culvert and sewer pipes are technically feasible from a production standpoint. However, only sanitary sewer products appear to be economically viable as the culvert and conventional storm sewer applications appear to be well served by products currently on the market. Based on the successful performances of packer-head specimens in pressure and there edge bearing tests, it was recommended that research be continued in the development and commercialization of packer-head production techniques for sanitary sewer pipe.